# FEASIBILITY OF USE OF REAL TIME LOCATION SYSTEMS ON THE CONSTRUCTION JOBSITES

BY

**WALEED UMER**

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**Thesis Committee**

Dr. Mohsin Khalid Siddiqui (Advisor)

Prof. Dr. Abdulaziz Bubshait (Member)

Dr. Bambang T. Suhariadi (Member)

Dr. A. Al-Ofi

Departmental Chairman

Dr. Salam A. Zummo

Dean of Graduate Studies

29/12/14

Date

**IN THE NAME OF ALLAH, THE MOST BENEFICIENT, THE MOST MERCIFUL**

*Dedicated To*

**My respected parents, teachers and friends whose care, love and guidance have been enlightening my life since my first breath.**

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| LAN | Local Area Network |
| Wi-Fi | Wireless Fidelity |
| RTLS | Real Time Location System |
| UWB | Ultra Wide Band |
| GPS | Global Positioning System |
| RFID | Radio Frequency IDentification |
| VR | Virtual Reality |
| AOA | Angle of Arrival |
| TDOA | Time Difference of Arrival |
| WLAN | Wireless Local Area Network |
| RF | Radio Frequency |
| LOS | Line Of Sight |
| NLOS | Non-Line Of Sight |
| PSM | Physiological Status Monitoring |
| ECG | Electrocardiograph |
| POE | Power over Ethernet |

# ABSTRACT (ENGLISH)


**NAME:** **WALEED UMER**

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Location tracking of the construction resources has proven itself advantageous over the period of time. By knowing the location of a resource, multiple benefits can be reaped which include progress monitoring, solving spatial conflicts, productivity analysis, ensuring safety, accidents prevention, proximity monitoring and project control. Real Time Location System (RTLS) can provide location data of the resources in real time. With help of RTLS, real-time monitoring can be done and actions can be taken in real-time. Many technologies have been used for RTLS which include GPS, WLAN, Zig-Bee, RFID, video-camera based RTLS and Barcode technology

Recent addition to the list is Ultra Wide Band (UWB) based RTLS. UWB employ Radio Frequency (RF) for its functioning. In a recent past, a lot of work has been done on employment of UWB based RTLS on construction sites. Literature has also highlighted various applications and systems which can be developed using UWB based RTLS. However there is still a need to work on feasibility of the RTLS. Specifically the effect of update rate, geometrical configuration of the system on the accuracy of the system and

man-hour requirement for deployment is unheard. This thesis work is directed in this direction.

A series of experiments were performed to study the feasibility of a commercially available, off the shelf RTLS on the construction jobsites. The objective of the work was on feasibility in terms of accuracy analysis of the system for various construction field scenarios on a large open site, man-hour requirements for repetitive deployment of the system and construction site specific protocols for the deployment of the system. Based on the experimental results and hands-on experience on the system, it can be concluded that the commercially available RTLS (Ubisense) is feasible for various field scenarios for critical project activities, offsite fabrication and fabrication yards instead of whole of the construction site. While the recommendations made on the basis of hands-on experience should be adopted for better results and accuracy of the system.

# ملخص الرسالة

**الاسم: وليد عمر**

**العنوان: دراسة جدوى استخدام نظام موقع الزمن الحقيقي (RTLS) في المواقع الانشائية**

**الرئيسية: هندسة وادارة التشييد**

**التاريخ: تشرين ثاني - 2014**


لقد أثبت تتبع مواقع موارد البناء نفسه مع مرور الوقت، فمن خلال معرفة مكان وجود إحدى هذه الموارد يمكننا الحصول على جملة من الفوائد التي تتضمن مراقبة تقدم العمل، إيجاد حلول للنزاعات المكانية، تحليل الإنتاجية، ضمان السلامة، منع الحوادث، المراقبة عن كثب، وضبط المشروع. إن نظام موقع الزمن الحقيقي (RTLS)بإمكانه تزويد المستخدم ببيانات الموقع الخاصة بإحدى هذه الموارد في الزمن الحقيقي. بمساعدة هذا النظام فإنه يمكن مراقبة الزمن الحقيقي وبالتالي بالإمكان إتخاذ إجراءات معينة في الوقت الحقيقي. لقد تم استخدام تقنيات تكنولوجية كثيرة لهذا النظام بما فيها GPS, WLAN, Zig-Bee, RFID بالإضافة إلى كاميرا الفيديو التي تعتمد أساسا على هذا النظام وأخيرا تقنية الباركود.

لقد تم حديثا إضافة تقنية أخرى إلى هذه القائمة وهي تقنية الباقة الواسعة جدا (UWB) المبنية على أساس هذا النظام، حيث تستخدم هذه التقنية ترددات الراديو لأداء مهامها. في الماضي القريب كان يتم إنجاز الكثير من العمل من خلال استخدام هذه التقنية في مواقع البناء. وقد أبرزت الدراسات السابقة كثيرا من التطبيقات والأنظمة التي بالإمكان تطويرها باستخدام هذه التقنية. لكن على الرغم من ذلك لا تزال هناك حاجة للعمل على جدوى نظام (RTLS) وعلى وجه التحديد تأثير معدل التحديث والتكوين الهندسي للنظام على دقة النظام نفسة إلى جانب المتطلبات التطويرية لساعات العمل المطلوبة. ولهذا الغرض فقد تم توجيه هذه الأطروحة بهذا الإتجاه.

لقد تم إجراء سلسلة من التجارب لدراسة الجدوى المتاحة تجاريا لنظام (RTLS) في مواقع البناء. كان الهدف من العمل قائم على الجدوى من ناحية تحليل دقة النظام لمختلف سيناريوهات مجال البناء في موقع كبير ومفتوح بالنسبة ل ساعات العمل المطلوبة للنشر المتكرر للنظام إلى البروتوكولات الخاصة بموقع الانشاء لنشر هذا النظام. استنادا إلى النتائج التجريبية والخبرة العملية من التعامل مع هذا النظام فإنه يمكن استخلاص أن نظام (RTLS) المتوفر تجاريا مجدي لمختلف سيناريوهات الموقع الخاصة بالفعاليات الحرجة للمشروع اصافة الى التصنيع خارج الموقع وفي افنية التصنيع الخاصة بدلا من الموقع الإنشائي ككل. في حين أن التوصيات التي بنيت على أساس الخبرة العملية ينبغي اعتمادها من أجل ضمان نتائج أفضل ودقة نظام أعلى.

# CHAPTER 1

# INTRODUCTION

Technology enabled jobsites have the potential of fundamentally altering the business processes on construction jobsites. Data Sensing and Analysis techniques can enable decision makers to make informed decisions in support of management of day to day construction operations. Recent researchers have identified construction safety and productivity as two main knowledge areas where data sensing and analysis can have an impact(Gerber et al. 2014). Information and data requirements in support of these knowledge areas mainly consist of locations of different assets and materials. Various technologies have been reported in literature to ascertain these locations with different levels of accuracy and timing.

Manual onsite data collection is time consuming, prone to errors, and is a tiresome activity. Real Time Location Systems (RTLS) have been used to collect accurate location data in real-time (Khoury and Kamat 2009). Real-time location data can help in preventing accidents on a construction site(Zhang and Hammad 2012). The availability of real-time location data of workers and equipment can prevent potential collisions and falling from height accidents (Maalek 2013). Material and equipment tracking is also of vital importance. The losses due to equipment and tools theft were estimated as $1 billion in United States for the year 2001 (Mcdowall 2006).

Hwang et al. (2004) reviewed diverse location sensing technologies and discussed the challenges that need to be addressed for their successful deployment. The technologies studied included Radio Frequency IDentification (RFID), embedded sensors, Global Positioning System (GPS), Flash LADAR, LASER Scanner, high-resolution video camera, digital photogrammetry and wireless communication. Researchers categorize these technologies based on the operating principle and are group under vision or communication based technologies. Vision based sensors require line of sight for accurate performance and are limited in their working range (Hightower and Borriello 2001). Communication based technologies provide longer working ranges but are prone to signal interference from other sources and environmental factors prevailing on jobsites. Ultra Wide Band based RTLS have shown to be more accurate as compared to tradition RFID and GPS based sensing for determining locations on jobsites (Ward 2007).

Research in the potential use of UWB is an active area where researchers have reported proof of concept studies in different construction related settings. Researchers have explored the accuracy with which UWB can operate on construction jobsites in different settings (Saidi et al. (2011), Cheng et al. (2011), Cho et al. (2010), Shahi et al. (2012), Rodriguez et al. (2010), Mok et al. (2010), Khoury and Kamat (2009) and Maalek (2013)). Knowledge and operation domains studied for UWB include safety and productivity of construction resources (Castro-Lacouture et al. (2007),Carbonari et al. (2011),Teizer et al. (2008),Teizer and Castro-lacouture (2007) and Cheng et al. (2013)), tracking and visualization of assets including workforce, equipment and materials (Teizer et al. (2007), Cheng and Teizer (2013), Shahi et al. (2013), Krishnamoorthy(2014) and Venugopal et al. (2010)), safety of critical equipment such as cranes (Hwang (2012) and Zhang et al. (2010)).

However, existing research sparingly discusses deployment protocols or practical accuracy requirements for Location Systems for adequate support of knowledge domain functions. Significant improvements can be achieved for Material Tracking even with lower levels of accuracy (Caldas et al. 2004) however feasible deployment of safety alert systems requires a higher level of accuracy of the underlying location system. Researchers in the construction domain have used average accuracy in scaled experimental settings as an indicator of the performance of commercially available UWB systems. Average accuracy may be suitable for productivity related operations however the authors believe that the average measures are deficient for construction safety purposes. This research uses a higher threshold of accuracy performance in a large experimental setting (approximately 1500 $m^2$) to demonstrate the feasibility of the use of a UWBRTLS on construction jobsites. Further the effect of change in configuration of the sensors is unknown (Maalek 2013). Unlike manufacturing domains where a system is deployed once, calibrated, and then used for extended periods of time, the author envisions that practical field deployments of UWB systems on construction jobsites would entail frequent and temporary deployment of sensing systems. The research reports results from repeated deployment of UWB system to establish protocols for field deployment from a construction perspective.

The thesis proceeds with an extensive review of the literature and identifies knowledge gaps from a deployment perspective. A commercially available UWBRTLS was used and the deployment protocols for that system are presented next. The thesis proceeds with a detailed description of the experimental setting and setups that were conducted. Results and conclusion are presented in the end.

## 1.1 ULTRA-WIDE BAND (UWB) TECHNOLOGY

UWB is relatively a new Radio-Frequency (RF) based technology. It utilizes 3.1-10.6 GHz frequency bandwidth. Because of such a large bandwidth, Angle of Arrival (AOA), Time of Arrival (AOA), Line of Sight (LOS) and Non-Line of Sight (NLOS) signals can be measured much precisely and accurately as compared to other RF based technologies (Muthukrishnan and Hazas 2009). UWB based real-time location systems use Time of Arrival (AOA), Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) methods for estimating the location of the resource being tracked (Maalek 2013). AOA describes the exact time at which the signal from an emitter is reached at the receiver. NLOS signals are different from LOS because LOS signals reach the receiver directly without striking any surface while NLOS signals are received after reflection from one or many surfaces usually metallic. AOA describes the angle at which the signal is received. This helps in estimating the location of the signal emitting device. TDOA method of location estimation utilizes time difference in arrival of a signal at different receivers.

## 1.2 ULTRA-WIDE BAND BASED RTLS

There are many commercially available RTLS based on UWB technology. The one which is being used in this research is manufactured by Ubisense. The RTLS under study consists of radio signal receivers called sensors, radio signal emitters are tags, Ethernet cables, Power Over Ethernet (POE) device which supplies power to the system and a platform for location estimation i.e. personal computer or a laptop. Figure 1.1 shows the sensor and Figure 1.2 shows the tag of the RTLS.

**Figure 1.1 Sensor of the RTLS** (Maalek 2013)

**Figure 1.2 Tag of the RTLS** (Maalek 2013)

Figure 1.3 shows the basic setup of the Ubisense RTLS. Out of many sensors/receivers, one is designated as Master Receiver which is used for synchronization of the timing data from the other sensors and a reference for calculations. Other receivers are termed as slave receivers. Timing cables are ethernet cables which are used for Time Difference of Arrival (TDOA) calculations. If these cables are not used then the system will do calculation on basis of Angle of Arrival (AOA) only.

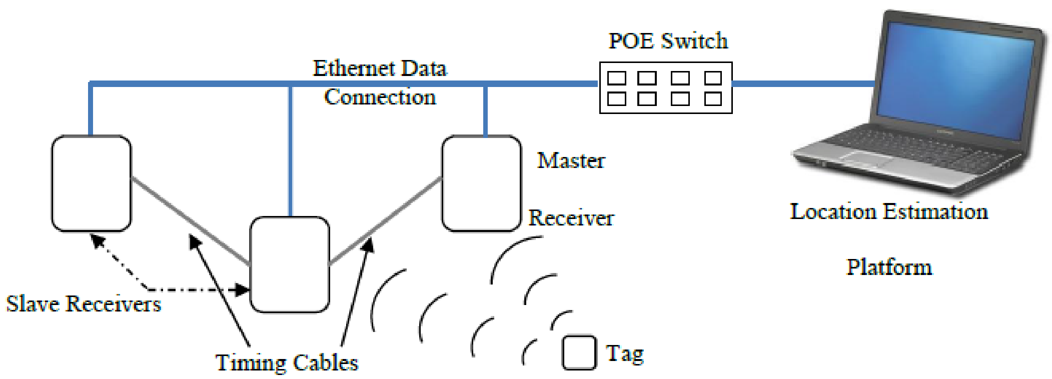


Figure 1.3 Setup of Ubisense RTLS **(Maalek 2013)**

Either AOA method alone or combination of AOA and TDOA can be used for location estimation. Table 1.1 shows the effect on accuracy for different options.

**Table 1.1 Different methods and accuracy obtained**(Rodriguez et al. 2010)

| Location method | Number of sensors detecting tag | Other information required | Result |
|---|---|---|---|
| Single-sensor AOA | 1 | Known height of tag | 2D horizontal position (+ known height) |
| AOA | 2 or more | None | 3D position |
| **TDOA+AOA** | **2 or more** | **None** | **3D position (highest accuracy)** |

## 1.3 AIM AND OBJECTIVES OF THE RESEARCH

The aim of the research is to do a feasibility study on RTLS. By feasibility, it means investigating the following research objectives:

I. To find out man-minutes requirements for implementation of RTLS on a construction jobsite.

II. To investigate accuracy parameters for different configurations for various construction field scenarios.

III. To describe and explain the construction specific protocols and challenges for implementation of the system.

## 1.4 STRUCTURE OF THE THESIS

To accomplish the research aim and objectives, a comprehensive literature review was done in order to find out knowledge gaps in the domain area. The literature review is discussed in CHAPTER 2 along with the gaps found in the previous research work.

CHAPTER 3 discusses the methodology adopted for the experimental research work. The results are shown in Chapter 4, and discussed in Chapter 5.Chapter 6 concludes the work with conclusions and recommendations for the research work consummated.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter discusses the previous research work done on UWB based RTLS for construction industry. The research done can be classified into two branches namely performance evaluation of the RTLS for construction sites and domain applications of the RTLS in construction industry. Many of the researchers have added knowledge to the both fields, which is why it is difficult to divide the literature review in distinctive parts.

## 2.2 LITERATURE REVIEW

Rodriguez et al. (2010) described the various prospective applications for RTLS in order to improve productivity and safety. The authors described the general requirements for deployment of Ubisense RTLS. Finally they tested the system on a construction site. The data gathered from the system was imported to a Geographical Information System (GIS) database. This allowed them to visualize the data as points or to form a trace of a worker carrying RTLS tag. 2D and 3D data gathered from the site was compared and analyzed to determine the appropriate layout of the jobsite for the minimum movements required to complete the job task.

An idea of 4D visualization (3D plus Time) of site activities is proposed by merging 3D CAD model and RTLS (Sadeghpour 2006). The RTLS proposed by the author is combination of Radio Frequency IDentification (RFID) tags and Global Positioning System (GPS). This merger will provide better visualization for site management and asset management, space-time conflicts. This can provide minute to minute update of the site activities and the resources which can greatly increase the efficiency of monitoring and control of the construction process.

Laboratory and field tests were arranged by Mok et al. (2010) to determined resources management capability and accuracy of UWB RTLS. The authors found UWB based RTLS is better in accuracy and performance than Wi-Fi and Zig-Bee technology. In indoor environments with square like geometry of the sensors, the mean deviation for x, y and z axis was 15cm. While for the outdoor environment, RTLS was tested in an underground tunnel for dynamic testing. The tunnel had poor geometry (rectangular as shown in Figure 2.1).

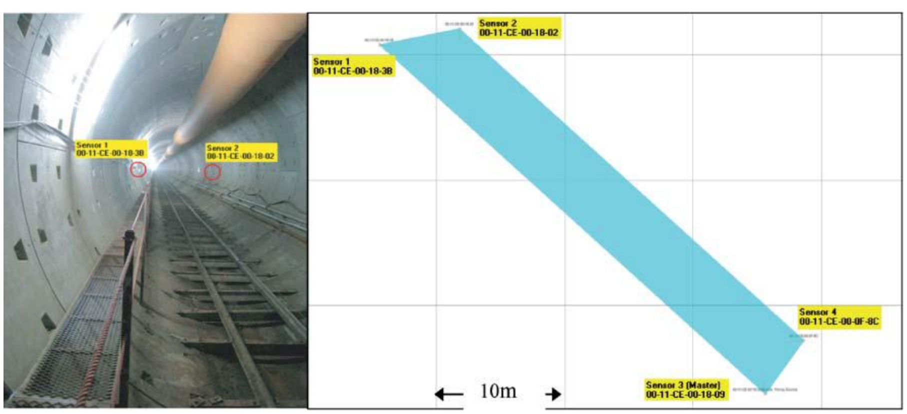


**Figure 2.1 Dynamic Testing of RTLS in an Underground Tunnel**(Mok et al. 2010)

The results were not satisfactory. Latter three improvements as following were made resulting to accuracy of 1m mean deviation from x, y and z axis.

I. Number of sensors were improved to 6 from 4

II. Data was filtered for those readings that were outside the geometry.

III. Calibration were made better by giving more attention to Pitch, Yaw and Roll

Pitch, Yaw and Roll define the orientation and rotation of the sensors in x, y and z direction. The authors concluded that better synchronization of the sensors of RTLS requires high quality LAN cables which are much expensive. Further the cable connectivity is not feasible for the complex and complicated construction projects.

A proactive safety system was developed by virtual fencing using UWB RTLS (Carbonari et al. 2011). Testing was done both in the field and real construction site. The system was developed using JAVA environment. Jordon Curve theorem was implemented for identifying the obstacles using polygons. Virtual fencing was done using computer applications. Figure 2.2 shows the system implemented in the testing laboratory. The inner rectangle as shown in Figure 2.2 represents the danger or alert zone. While the outer rectangle represents the caution/attention zone. The system alerts the worker as it moves from caution zone to the danger zone. Different paths were adopted to make sure that the system is working accurately. The Autoregressive model was implemented to improve localization accuracy. Data was collected and errors were removed from the system. Finally the system was implemented on a real construction site. The authors were convinced by the performance of UWB based RTLS.

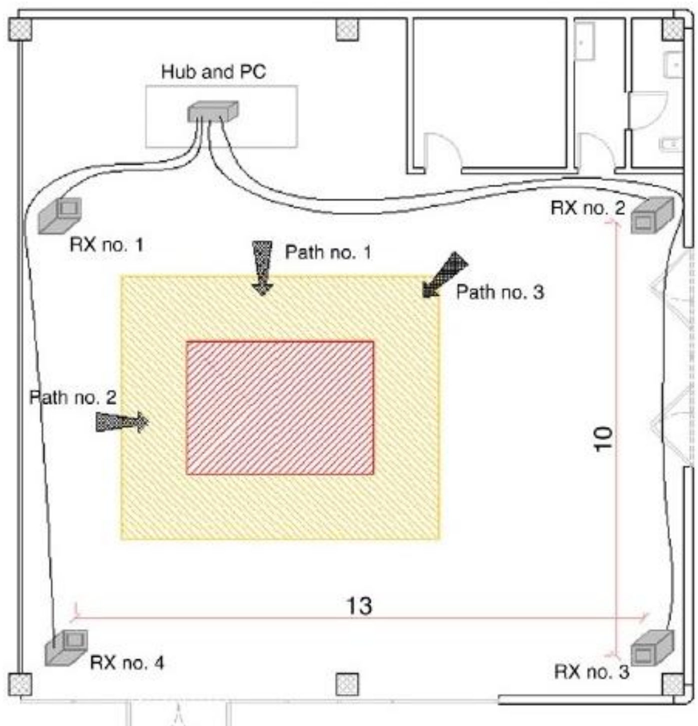


**Figure 2.2 Proactive Safety System** (Carbonari et al. 2011)

Using UWB based RTLS, the movement of workers was observed to avoid obstacles and to generate a safe path on a construction site (Teizer et al. 2008).The site was divided in cubes of 0.1x0.1x0.1 m. whenever a person wearing UWB tag passes through a cube, the system records and gives an increment to the number of passes through the particular cube. Now the site is visualized by different colors on basis of numbers of passes through each cube (see Figure 2.3). White color indicate no passes i.e. obstacles.

Color coding is shown in Table 2.1. Convex hull algorithm was used to identify the obstacle contours and encompasses the obstacle with a convex polygon. Hence finally shortest and safest path was obtained.

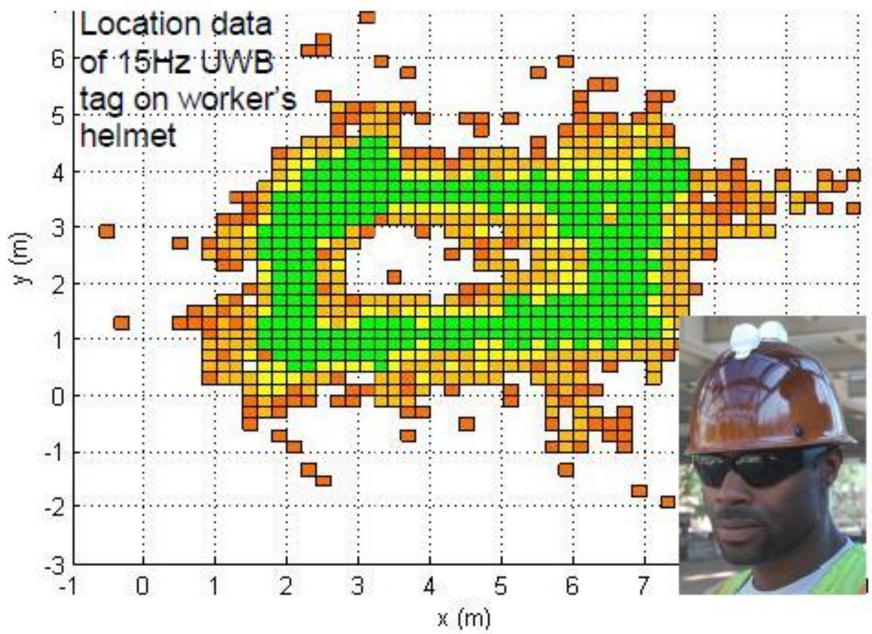


**Figure 2.3 Movement of a construction worker**(Teizer et al. 2008)

**Table 2.1 Color coding for the experiments**

| Cube Visits | Cube Colour | Safety |
|---|---|---|
| 0 | White | Very Low |
| 1 | Dark Orange | Low |
| 2-8 | Light Orange | Medium |
| 9-20 | Yellow | High |
| >20 | Green | Very High |

Although Real time location systems and physiological status monitoring (PSM) systems have been used alone in the past but data fusing had not been done before. Authors combined the data from RTLS and PSM to integrate physiological status of a construction worker and location data on a job site (Cheng et al. 2013). This information was used to monitor physiological health of a worker as he did his job task which included lifting the material, bending and squatting. PSM used in the research consisted of an electrocardiograph (ECG) sensor, a breathing rate sensor and a three-axial accelerometer. PSM was able to get the data without interrupting the work of a worker. Figure 2.4 shows the relationship among the time, heartbeat rate, body posture angle and unsafe motion for a construction worker. Figure 2.5 shows the integration of location data and body posture status for a small installation/decommissioning task. The body posture is classified either safe or unsafe. An angle of $+25^{o}$ was used to distinguish between standing and bending where $0^{o}$ was taken reference when a worker was standing straight

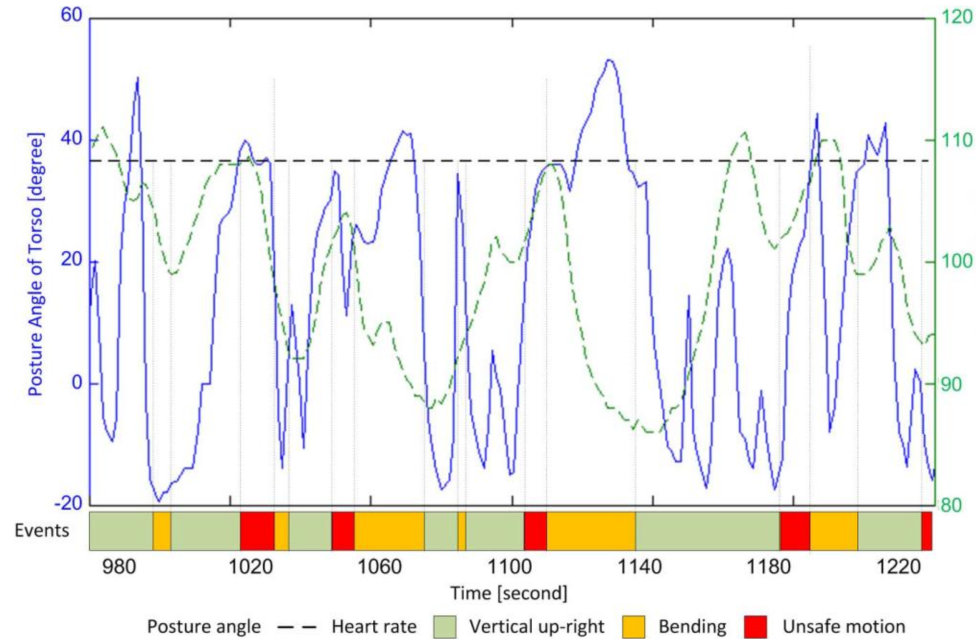


**Figure 2.4 Relationship among the time, heartbeat rate, body posture angle and unsafe motion**(Cheng et al. 2013)

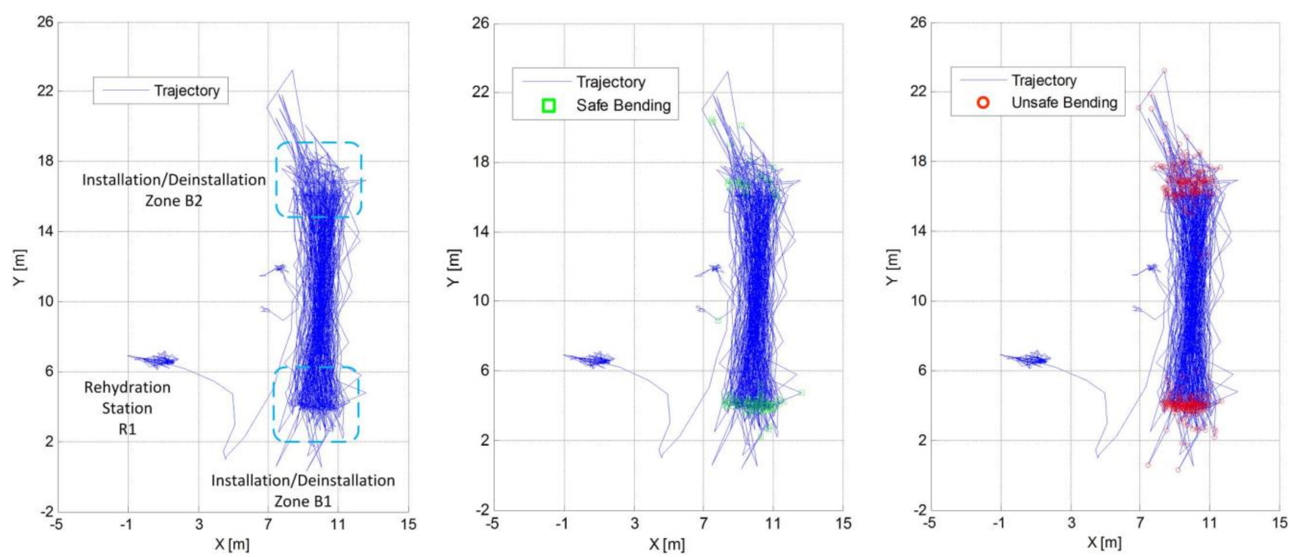


**Figure 2.5 Integration of location data and body posture status**(Cheng et al. 2013)

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Various computer applications were developed with C# using data which is provided by RTLS (Lee et al. 2009). Applications include path tracker, RTLS and efficiency meter e.t.c. The path tracker application collects real time location data coordinates and show the path of the track followed by the tag through data visualization.

Three experimental setups were arranged for Ubisense RTLS by Shahi et al. (2012)

I. Enclosure of tags in metal and wooden boxes was done in order to estimate the errors in location data. In metal boxes accuracy decreased substantially. When waves emitting tags of RTLS system were enclosure by 100%, the average error was 50 cm and the location was within 1m radius of the point which RTLS pointed with confidence level of 95%. For wooden boxes and no enclosure the average error in location estimation was below 15cm and location of point could be known with accuracy of 22cm radius with confidence level of 95%.

II. The system was tested in a laboratory where the line of sight was obstructed. The results showed decrease in accuracy around the boundary of the rectangle formed by the geometry of the RTLS sensors. Contour lines of the average errors are shown in Figure 2.6.

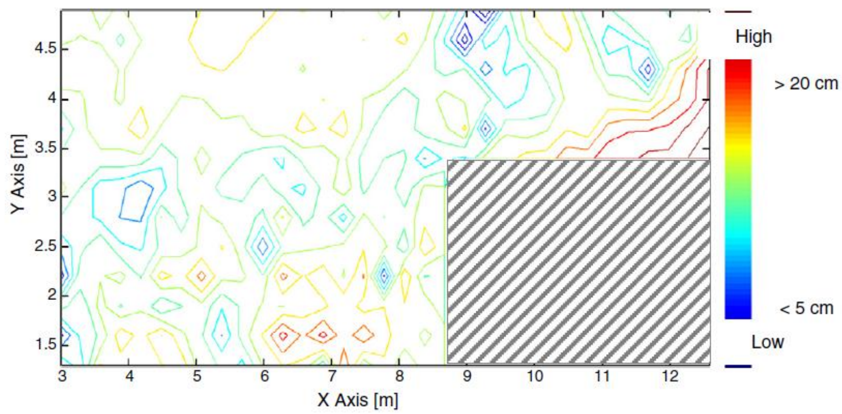



**Figure 2.6 Contour lines for the average errors** (Shahi et al. 2012)

III. The system was tested in a building project on 5th floor where there was immense ducting and piping work. The accuracy decreases as the congestion increased while the project was progressing. The authors concluded that the line of sight should be well maintained for better accuracy. Also the more spatial distribution of sensors is there for an axis, the better is accuracy of the system.

Another work done was un-tethered i.e. wireless connection in place of wired connection (Cho et al. 2010). This allowed easy deployment of the RTLS system on the congested construction site. Different conditions under which the UWB based RTLS was tested were open space, wooden, steel and fully furnished environment. Experimentation results showed slight decrease in accuracy of the location data for un-tethered network as compared to the cabled network. Both static and dynamic tests were performed. Authors found that human body adversely affects the accuracy of UWB based RTLS. Further they found that increase in height of the tag from ground level to around 1m showed improvement in accuracy of the location data as it improved line of sight among the sensors and the tags. The sources of errors are different in different environments such as electromagnetic interference and presence of electronic devices. From the data outliners were defined based on the principles of statistics. Finally they concluded that that with un-tethered networking of UWB based RTLS, the accuracy that can be attained is about 50cm in static conditions and 65cm for dynamic conditions for a dense construction site.

A system was developed to for real time collision free paths for crane movement (Zhang et al. 2010). Ultra Wide Band based RTLS was used for the purpose. Rapidly-exploring Random Trees (RRT) and Dynamic Rapidly-exploring Random Trees (DRRT) algorithms were used for path planning and re-planning respectively in real time. Autodesk Softimage 3D software was used to develop 3D visualization. Motion Strategy Library was used to develop collision free paths using RRT algorithms. Figure 2.7 shows the methodology adapted by the authors for path planning. Real time location data was acquired using UWB based RTLS. 3D model was developed using off the shelf product of Autodesk. Combination of these two provided updated environment at the site. Planning, re-planning algorithms were used along with operating rules for the particular jobsite to provide safe and collision free path for the updated environment. Hwang 2012 also showed that UWB is a potential technology for accident prevention in tower crane operations.

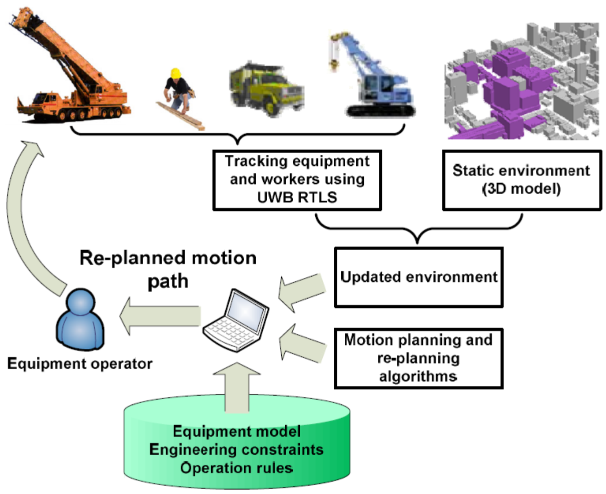



**Figure 2.7 Working of path planning system** (Zhang et al. 2010)

New type of monitoring system for construction activities is developed using RTLS (Shahi et al. 2013). Activities such as physical installation of beams and columns are easily detectable by traditional methods but activities like painting and welding are not monitored by traditional object-based tracking. A new approach was developed, each trade worker was provided with a unique coded RTLS tag which was turned-on as the activity at a certain point where an activity like welding was being done. The data was collected and after the activity was finished the tag was turned off and removed from the location. This data is used for as-built drawings. Accuracy was ensured using total station. Further the location data was compared with CAD drawings to compare as-built and design drawings. Finally error analysis was done.  Matlab was used for the programming purposes.

UWB based RTLS by Saphhire Dart was tested in outdoor construction environment (Cheng et al. 2011). The environment was a busy construction site with presence of many construction materials. The accuracy was confirmed with Robotic Total Station. A tag was attached to the resource to be tracked along with the prism so that the location can be verified. Different signal frequency tags were used based on the resource to be tracked. Stationary or the little moving resources were equipped with 1 Hz tag while the moving were equipped with 15, 30 and 60 Hz. The system was tested in a construction pit and material yard. The results showed that the system performed well for the material and resource tracking purposes. Further the authors studied the relationship between accuracy and distance among the sensors. The system was able to give an accuracy of 2m when the distance was increased to 270m. Authors were satisfied with the results as they found in the literature that this sort of accuracy is enough for material tracking in a yard.

In addition to these experiments the authors collected productivity data using RTLS based on the division on the construction site in to different areas. Figure 2.8 shows the results of the data that authors compiled.

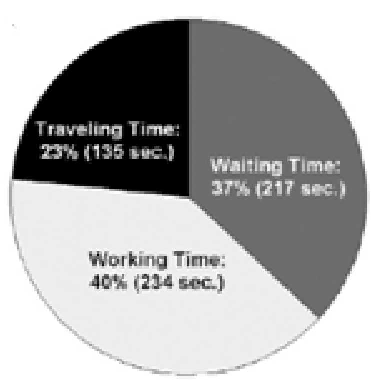



**Figure 2.8 Productivity data analysis**

Cheng and Teizer studied and applied fusion of Virtual Reality (VR) and Real Tile Location System (Cheng and Teizer 2013). They discussed its merits and potential capabilities. Firstly they elaborated virtual reality and finally applied the concept of combination of VR and RTLS to field construction works. VR is being used for the long time in construction industry but the use of real-time location data was never focused before. Various experiments were carried out to study the system. The information gathered enhanced the situational awareness and highlighted spatial conflicts in the jobsite. The authors concluded that this new approach can considerably improve productivity and safety standards. Figure 2.9 shows an image generated by the system. The red area is depicting unsafe working zone due to suspension of the load from a crane above. The tags above the workers show their distances from either from their respective work places or the mobile equipment.

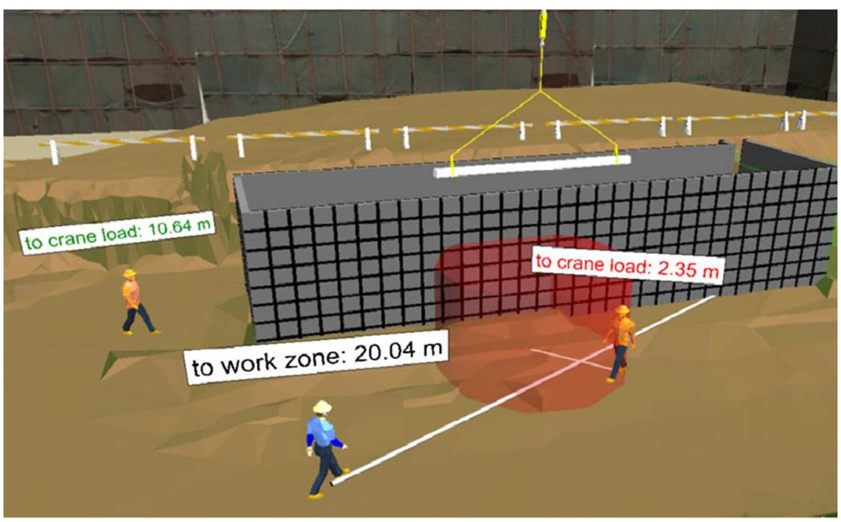



**Figure 2.9 Computer generated image for fusion of VR and RTLS** (Cheng and Teizer 2013)

Teizer and Castro-lacouture (2007) blended technologies to help in managing the work site more effectively. The combined imaging technologies and UWB to enhance the safety and productivity reporting on construction sites.

Saidi et al. also studied performance of a commercially available Ultra Wide Band RTLS (Saidi et al. 2011). Both dynamic and static experiments were studied. Robotic total station (RTS) was used as a ground truth to setup the experiments. The static experiments were performed in an outdoor area of 20m by 10m. For the static experiments, the authors studied the effect of changing the transmitters` height and calibration precision on the accuracy of the real time. Increase in the transmitters` height yielded better results for accuracy. For calibration precision, better calibration (Robotic Total Station as compared to GPS with accuracy of 20 to 30cm) led to better accuracy.

Figure 2.10 and Figure 2.11 show the comparison between standard deviation for two similar experiments where the only difference was calibration precision. Figure 2.10 shows the contour plot for standard deviation when the calibration was done using RTS with accuracy of 1mm. While Figure 2.11 shows the contour plot when the calibration was done using GPS with accuracy of 200mm.

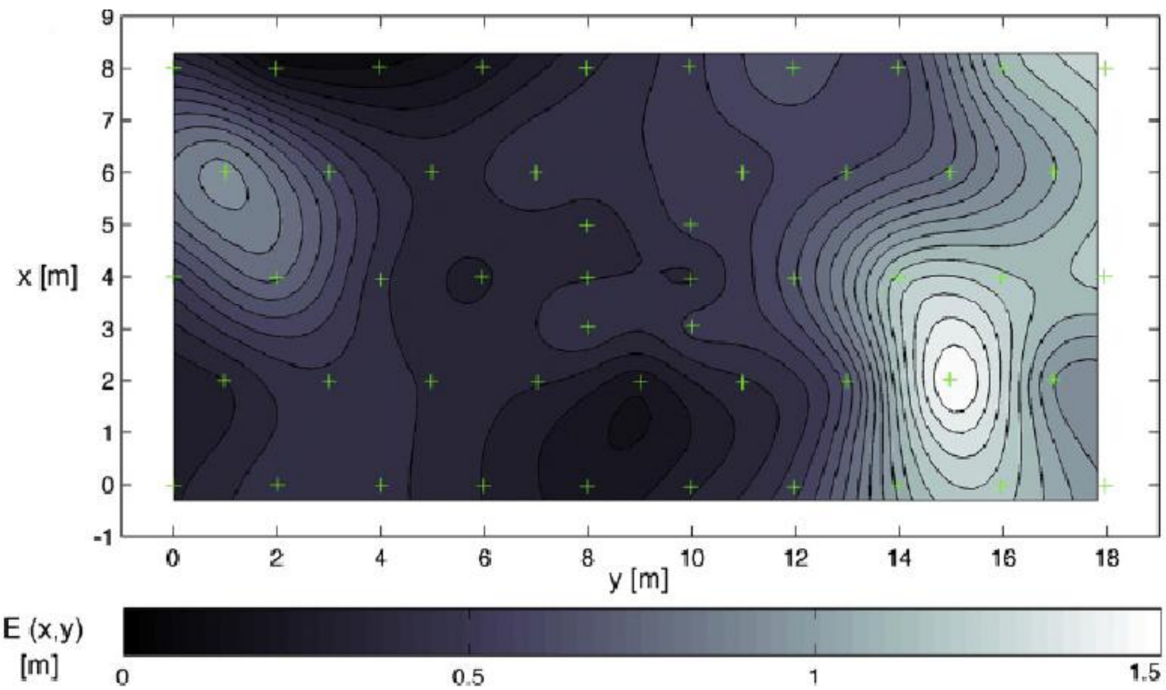



**Figure 2.10 Contour plot for standard deviation using RTS** (Saidi et al. 2011)

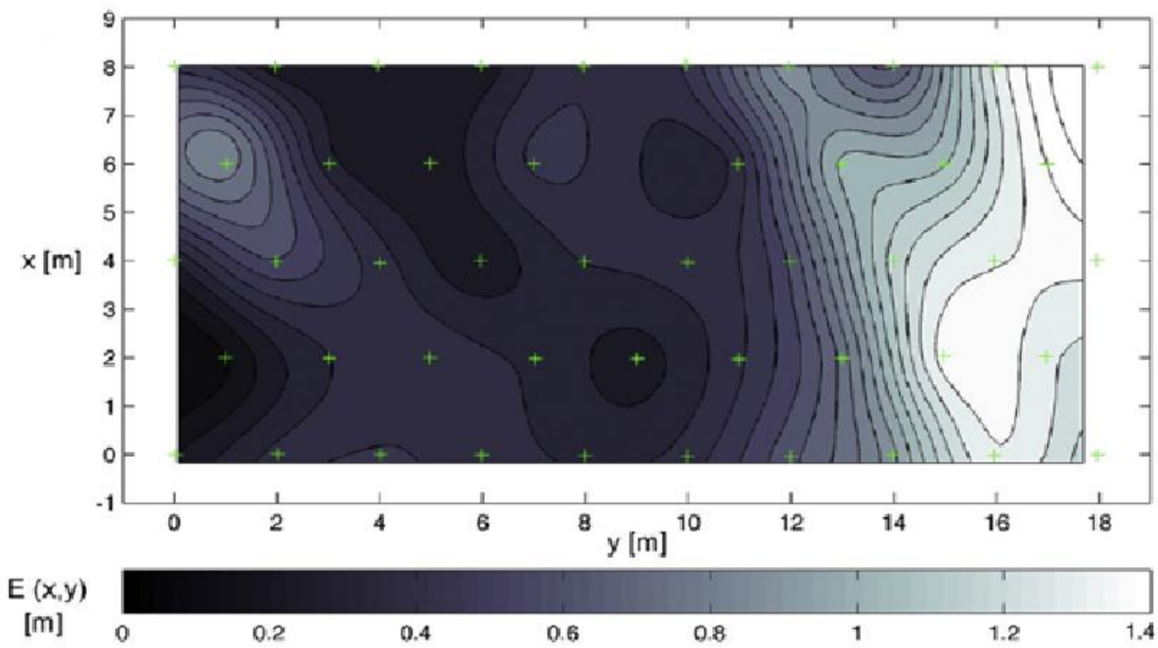



**Figure 2.11 Contour plot for standard deviation using GPS**(Saidi et al. 2011)

For dynamic experiments which were carried out in a large construction lay down yard, the RTLS was compared to robotic total station where RTS was used as ground truth. The authors concluded that the accuracy achieved was sufficient for the tracking and material location purposes.

A number of experiments were designed to test the accuracy of a commercially off the shelf UWB RTLS (Maalek 2013). The researcher explored the effect of many factors on accuracy including

I. Multipath effect.
II. Angle Of Arrival (AOA) method only in place of Time Difference of Arrival (TDOA) & AOA
III. Effect of number of radio waves emitting tags.
IV. Effect of number of the receivers.
V. Effect of a moving resource which is being tracked.
VI. Effect of the presence of metal surfaces.

Series of experiments were carried out in Mechanical Lab and a workshop. The workshop had different machinery and metals present, similar to a construction site. Both static and dynamic experiments were performed. For all of the tests, the system was able to deliver an accuracy of sub-meter.

Table 2.2shows summary of the experimental results. Distance Root Mean Square (DRMS) was used to assess 2D accuracy of the system while Mean Radial Spherical Error (MRSE) was used to investigate 3D accuracy of the RTLS.

**Table 2.2 Summary of the experimental results** (Maalek 2013)

| Type of Experiment | | Static Experiments | | | | | | Dynamic Experiments | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Variables | | Multipath reflection | Signal blockage | Metallic surface | Number of tags | Number of receivers | AOA | Velocity of tag | Number of tags | AOA | Static and dynamic tags |
| Laboratory Experiment | Experiment carried out | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes |
| | Average DRMS (cm) | 24 | 33 | 15 | 34 | 14 | 27 | 23 | 26 | N/A | 17 |
| | Average MRSE (cm) | 60 | 65 | 30 | 60 | 26 | 37 | 28 | 41 | N/A | 38 |
| Workshop Experiment | Experiment carried out | No | No | No | Yes | No | Yes | No | No | Yes | No |
| | Average DRMS (cm) | N/A | N/A | N/A | 33 | N/A | 39 | N/A | N/A | 48 | N/A |
| | Average MRSE (cm) | N/A | N/A | N/A | 59 | N/A | 54 | N/A | N/A | 62 | N/A |

The author concluded that the system can provide sufficient accuracy in multipath environment and presence of metals for tracking purposes on a construction site. Further the system was capable to track the resources even only Angle of Arrival method is used. Also the RTLS could perform satisfactorily for tracking moving resources and tracking multiple resources at a time.

## 2.3 KNOWLEDGE GAP

The literature review shows potential prospects of UWB RTLS for construction sites. But the thing under question is that what are requirements to achieve such accuracy, how much effort is to be put-in, for which domain the system is suitable for, what risks are involved in deployment e.g. safety challenges because of the system itself.

Experiments mentioned in literature review were scaled experiments. Cheng et al. (2011)tested the system on a site of 40x30 m using 7 sensors. Saidi et al.(2011) deployed the system on 20x10m site using 6 sensors. Mok et al. (2010) tested the system on 30x5m site. Shahi et al. (2012) performed the experiments on 9x3m site. Construction sites are usually much bigger in size. Experiments performed on smaller scale may provide good accuracy but it is necessary to investigate the accuracy at a large site. The manufacturer of the RTLS (Ubisense) suggests maximum distance between the sensor (which receives radio signals emitted by tag) and tag (small radio emitting device which is to be tracked) to be 50-70m in case of free line of sight. However our chosen site had 4 metal light poles in the test area. Considering this thing in mind along with initial experiments` results, we decided to investigate the system on an area of 40 x55 m approximately.

As described above, the area under investigation was small and some of the previous researchers used up-to 7 sensors on their experimental fields. This resulted in high sensor density resulting exaggerating the accuracy in their results. So without testing the system on a large scale with low sensor density, claiming the system to be beneficial for construction industry is a mere a proof of concept. We tested the system on larger scale with only 4 sensors resulting lower sensor density in the test area. Further the effect of change in configuration of the sensors is unknown (Maalek 2013). We also investigated this change.

With the system deployed on the site, new safety hazards arise on the construction site. None of the previous work has highlighted these hazards. We have come up with identification of these hazards and how these hazards can be minimized. Further Maalek (2013) noted down deployment time required for installation of the system but time alone is not the indicator for effort put in for installation. Man-minutes is a better option to describe such data. Also for outdoor construction work, the system is deployed and packed; again and again as the system cannot be left on the site as a safety concern both for the assets and the system itself. We deployed the system multiple times to study whether the learning effect exists or not. We measured the effort in term of man-minutes as it is a better indicator for effort to be put in.

Although the manufacturer provide general detail about the deployment protocols of the system but these protocols are general in nature for all industries. Based on our hand on experience of the system we have described the protocols to be specifically for construction industry. Last but not the least previous accuracy analyses by the various researchers have investigated average accuracy for the system. This approach may prove fruitful for domains such as material tracking and theft preventing e.t.c. but in case of personnel safety average accuracy may exaggerate the accuracy achievements of the system and may not prove helpful on the construction site. In addition to average accuracy we have also investigated 95th percentile for accuracy which is more reliable while decision making when the system is to be deployed for the safety purposes.

# CHAPTER 3

# EXPERIMENTAL PROTOCOLS AND PROCEDURES

## 3.1 INTRODUCTION

This chapter discusses the protocols and procedures adopted for deployment of the RTLS on a test site. Firstly, the layout of the test site is discussed. Then the experimental variations are discussed. These variations are based on actual scenarios which could happen at actual construction site. Three sort of cell configurations are discussed focusing on the access permission or other dictating parameters. They include full-site access, partial-site access and offsite setup. For each setup there are two possible conditions i.e. either the system will be cabled setup providing maximum input for location estimation, hence providing better performance or wireless setup, which can be deployed when the wiring is restricted or cannot be used because of any other reason/s. Then construction sites specific protocols are discussed which were followed while deploying the system repetitively. In the end mathematical basis for accuracy, precision and offset are discussed for 2D and 3D location data.

## 3.2 SITE LAYOUT

The feasibility of use of Real Time Location Systems on the construction jobsites greatly depends on the accuracy of the data these systems can provide in real-time. To assess the accuracy of RTLS, a series of experiments will be carried out in open environment. Experiments are performed to simulate the actual construction site conditions and testing the system, setting performance as a criterion. An open area was selected for the experiments. The laser scan image for the site selected is shown in Figure 3.1. The dimensions of the site were around 40m x 55m because sensors were placed 5m beyond the boundary of the area shown in the figure.

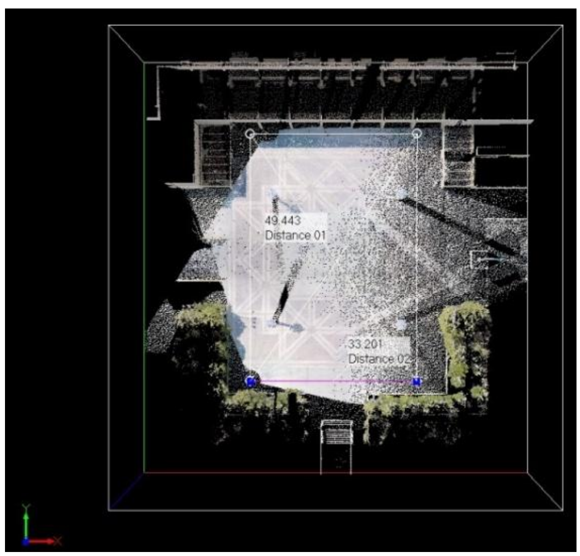



**Figure 3.1 Layout of the Experimental Site**

## 3.3 CELL CONFIGURATIONS

Three setups or cell configurations are considered for the experimental runs based on the site access. These three configurations are discussed as below:

### 3.2.1 FULL SITE ACCESS

This cell configuration is made for site conditions where full access to the site is available. Four sensors are spread in the corners. This will fulfill the requirements for optimum accuracy at the construction site. This configuration is shown in the Figure 3.2.

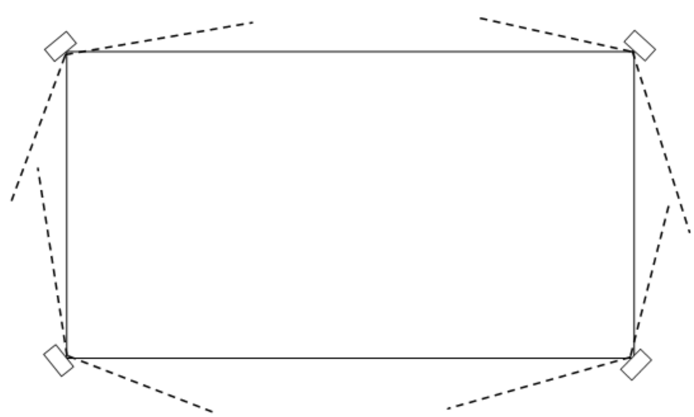


**Figure 3.2 Cell Configuration for Full Site Access**

### 3.2.2 OFFSITE SETUP

This cell configuration is considered for cases where the access to the construction is either not feasible or not granted. The sensors will be placed outside or at the one boundary of the construction site. This will lead to the accuracy of the real time location data for the cases when data collection is done off-site. The setup is shown in the

Figure 3.1.

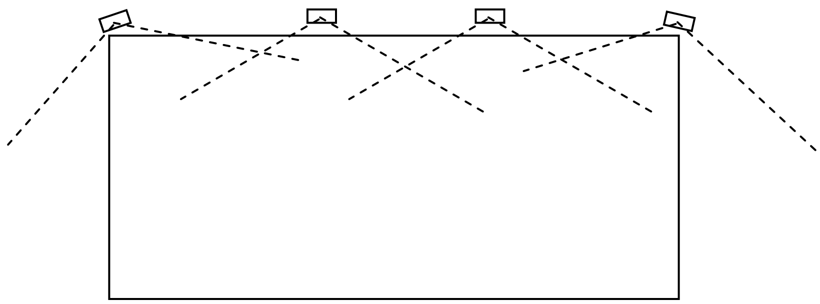


**Figure 3.3 Cell Configuration for Offsite Setup**

### 3.2.3 PARTIAL SITE ACCESS

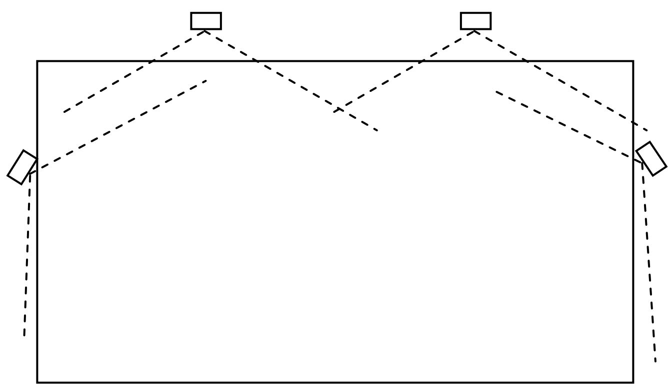


**Figure 3.4 Cell Configuration for Partial Site Access**

This cell configuration is considered for the cases where the full access for the site is not available. The sensors will be deployed on the partial site. The setup is shown in the Figure 3.4.

## 3.4 EXPERIMENTAL SETUPS

For each of the cell configuration, the accuracy of the real time location systems will be assessed by two ways:

1. Cabled Network of the Sensors
2. Wireless Network of the Sensors

For the cables network, the tracking of the resources will be done using both Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques. For such setups, wires are needed to be run on the construction jobsite. Running the wires on the construction site will have certainly some implications but this sort of setup will enhance the accuracy of the real time location system.

For the wireless network, the localization method will be only relying on the Angle of Arrival technique. Such a setup may provide inferior accuracy as compared to the cabled network but this will provide and edge of wireless communication of the system. Such systems can be deployed easily at the construction sites with certainly less complications.

In order to study feasibility of the Real Time Location Systems, it is necessary to measure the number of man-minutes required to setup the location system. For more precise analysis the setup is broken in three steps which are as follow:

1. Man-minutes requirement for Layout and Cabling
2. Man-minutes requirement for Orientation & Survey
3. Man-minutes requirement for Calibration
4. Initiation of Monitoring

### 3.3.1 MAN-MINUTES REQUIREMENT FOR LAYOUT AND CABLING

This step involves deployment of the system`s hardware on the construction site. Firstly the location of sensors will be decided based on the coverage required for the site, access to the site, site`s work environment and other factors. This information will lead that whether the sensors are to be deployed on the site or offsite. Also this will dictate that whether the sensors are to be mounted on the walls of the construction site or tripod stands are to be used. Walls are preferred than tripod stands because of the following reasons:

- Walls are much firm and stable than the tripod stands which are more prone to vibrations and winds on the construction site.
- Walls are usually safer than tripod stands. Cranes and other mobile equipments may hit the tripod stands.
- Tripod stands may fall causing damage to the sensors.

Then the hardware sensors will be deployed.  For the sensors to be mounted on the wall, wall mountings are to be installed. For tripod stands, the sensors will be placed on the stands.

For utilization of the RTLS using both AOA and TDOA methods, a cabled network is necessary. Considering the cabled network, the wires are needed to be run among the sensors and from a Master sensor to the computer. A Master sensor is that sensor which is designated as a reference for Time Difference of Arrival measurements. Power can either be provided to the sensor through DC supply or by Power over Ethernet (POE).

For these steps of layout and cabling, man-minutes consumed will be noted in order to calculate time and cost requirement for these steps. Time and cost requirement will vary from site to site depending upon the area to be covered and distinctive site characteristics for each construction site such as congestion, obstacles in sight of view, presence of nearby electronic equipment e.t.c.

### 3.3.2 MAN-MINUTES REQUIREMENT FOR ORIENTATION & SURVEY

Once the layout and cabling is done, the next step is to adjust the orientation of the sensors and do a survey for the site. Here survey refers to find out the location of the sensors and one or two reference points (for calibration). While adjusting the orientation of the sensors, it must be kept in mind that the coverage which a sensor (manufactured by Ubisense) can provide is $110^o$ in front horizontal plane and $90^o$ in the vertical plane.

After the orientation adjustment, the survey needs to be done in order to know the location of the sensors in x, y and z axes. This can be done using various available surveying equipments like total station or laser scanner. Further the man-minutes are also dependent upon

- Number of sensors to be surveyed
- Site characteristics
- Surveying equipment

The accuracy of survey depends upon the necessity and the surveying equipment being used. More accuracy will require more man-minutes to be consumed.

### 3.3.3 CALIBRATION

There are various methods of calibration that can be adopted. These methods are recommended by the RTLS manufacturer (Ubisense in our case).

For our experiments, multiple control points will be established in the test area. These control points will be around 20 to 30. These will be spread in the whole area and their exact location will be determined using surveying equipments. Also for the calibration part, man-hours requirement will be noted.

### 3.3.4 INITIATION OF MONITORING

Before initiation of monitoring using RTLS, UWB incident power plot is adjusted. This makes sure that UWB noise present in the environment doesn't disturb the localization of the objects to be tracked. Finally the update rates are adjusted for the tags based on the purpose and representation of the object for which they are being used. Further data logging is started in order to get record of the position co-ordinates for post analysis.

In addition to the basic stuff filters can be applied to the system which helps in accurate localization based on the conditions of the object being tracked. For example Static filters help in accurate localization of non-moving objects while Information-Filtering filter helps in determining accurate location for the objects in motion.

Further many relationships among the objects can be defined for assisting the various tasks including restricting the objects in certain area and notifying if object cross the limits.

## 3.5 DRMS AND MRSE

On construction sites, some assets are static for most of the time, thus we need their location update at lesser update rate. While other assets are mobile and we need continuous location update for these resources. So two sets of experiments will be performed for each setup; static and dynamic; simulating the field conditions for these assets. For the static experiments, the tags will be placed on the control points for few seconds. The average location parameters will be compared with the known survey parameters of that particular control point. This will enable us to assess the accuracy of the RTLS.

For the dynamic experiments, the movements of the workers or machinery will be decided prior to performance of the experiments. The layout of the pre-known path will be done and the path will be divided into small segments. Video capturing data, screen capture data for the computer along with the known location data for the movement path will be merged and inter related to know the accuracy of RTLS in dynamic experiments.

Distance Root Mean Square (DRMS) will be used to assess accuracy for 2D experiments. Whereas Mean Radial Spherical Error (MRSE) will be used to assess accuracy for 3D experiments. MRSE and DRMS allow to combine precision and offset in one single value to represent accuracy (Alfred Leick n.d.).

Mathematically,

$$DRMS = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{actual\,)}^{2}}{n} + \frac{\sum_{i=1}^{n}(y_i - y_{actual\,)}^{2}}{n}}$$

$$MRSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{actual\,)}^{2}}{n} + \frac{\sum_{i=1}^{n}(y_i - y_{actual\,)}^{2}}{n} + \frac{\sum_{i=1}^{n}(z_i - z_{actual\,)}^{2}}{n}}$$

Where n is the location data reading number for a point of interest. $x_i$, $y_i$ and $z_i$ location coordinates for the $i^{th}$ reading and $x_{actual}$, $y_{actual}$, $z_{actual}$ are actual coordinates of that particular point.

# CHAPTER 4

# FIELD EXPERIMENTS

## 4.1 INTRODUCTION

Field experiments were carried out as explained in the sections before. This chapter discusses specifically the experiments performed. Firstly the actual procedures followed are discussed and then the results of the experiments. Field experiments were performed at the open site. The site geometry was a rectangle. It had 4 lighting metal poles. Its surface was almost leveled. Around the site were concrete buildings. The experiments were performed numerous times at the same time over a period of time. Bench marks were used to make the repetitive deployment easy.

## 4.2 SITE LAYOUT FOR PERFORMANCE OF EXPERIMENTS

Figure 4.1 shows the layout of the site. 19 control points were established as shown. Approximate distances among the points are also shown. The control points were established to ensure that whole of the site is captured and measurements are collected throughout the site. To establish the control points, laser scanner was used to precisely locate the coordinates of a control point.

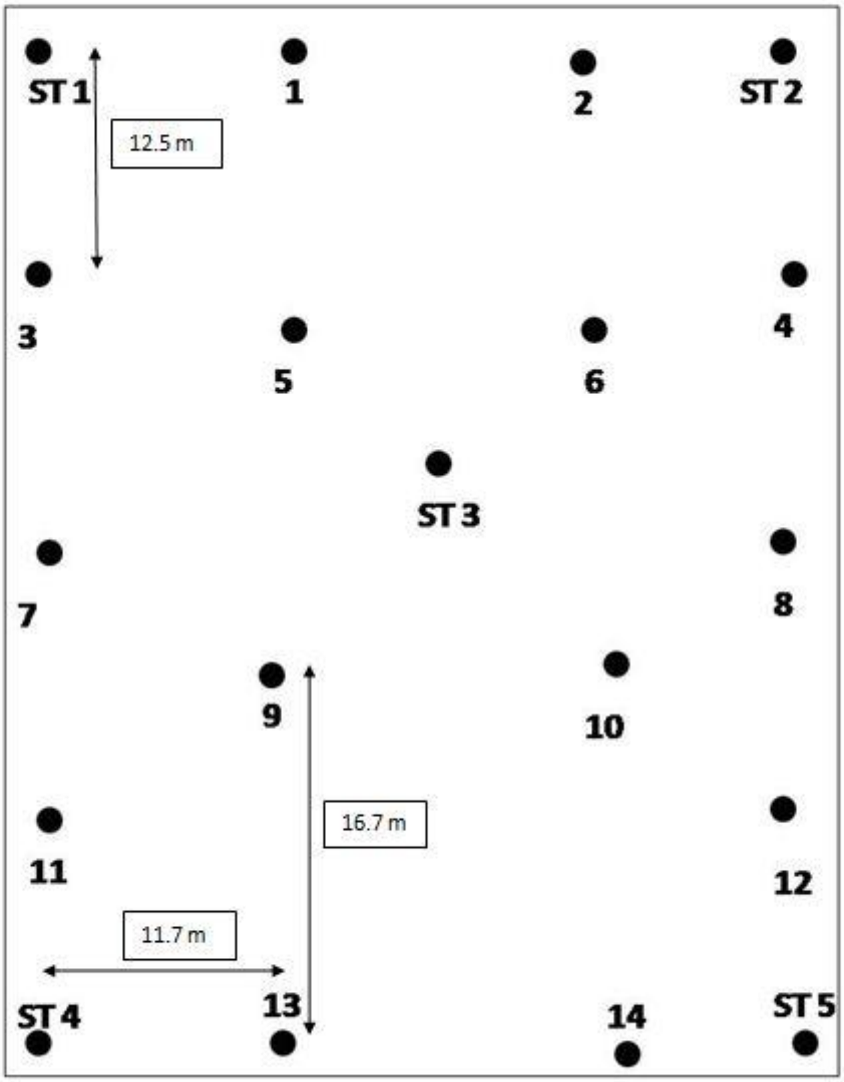



**Figure 4.1 Layout of the Experimental Area**

Figure 4.2 shows the laser scanner used for the purpose while

Figure 4.3 shows a target used to determine coordinates of a point with quite accuracy and precision.

**Figure 4.2 Laser Scanner** **Figure 4.3 Target for Laser Scanner**

All of the station points as shown in Figure 4.1were surveyed. Station 4 was designated as reference point where the x, y and z coordinates were taken as 0. Based on the description above; Table 4.1 shows the coordinates of all of the station points. All of the dimensions are in meters.

**Table 4.1 Coordinates of the Station Points**

| Points | X | Y | Z |
|---|---|---|---|
| PT01 | 11.922 | 49.35 | -0.015 |
| PT02 | 22.403 | 49.468 | -0.007 |
| PT03 | 0.068 | 36.726 | -0.104 |
| PT04 | 33.537 | 37.047 | -0.027 |
| PT05 | 11.925 | 32.933 | -0.076 |
| PT06 | 22.509 | 32.71 | -0.034 |
| PT07 | 0.121 | 24.182 | -0.227 |
| PT08 | 33.25 | 25.094 | 0.014 |
| PT09 | 11.355 | 16.652 | -0.049 |
| PT10 | 21.351 | 16.919 | -0.019 |
| PT11 | 0.106 | 11.979 | -0.115 |
| PT12 | 33.55 | 12.572 | 0.132 |
| PT13 | 11.131 | -0.051 | 0.108 |
| PT14 | 21.501 | 0.191 | 0.187 |
| ST-01 | 0 | 49.444 | -0.019 |
| ST-02 | 33.321 | 49.53 | -0.013 |
| ST-03 | 17.274 | 23.941 | -0.069 |
| ST-04 | 0 | 0 | 0 |
| ST-05 | 33.188 | -0.011 | 0.242 |

For dynamic experiments a zigzag path was chosen as shown in the Figure 4.4.

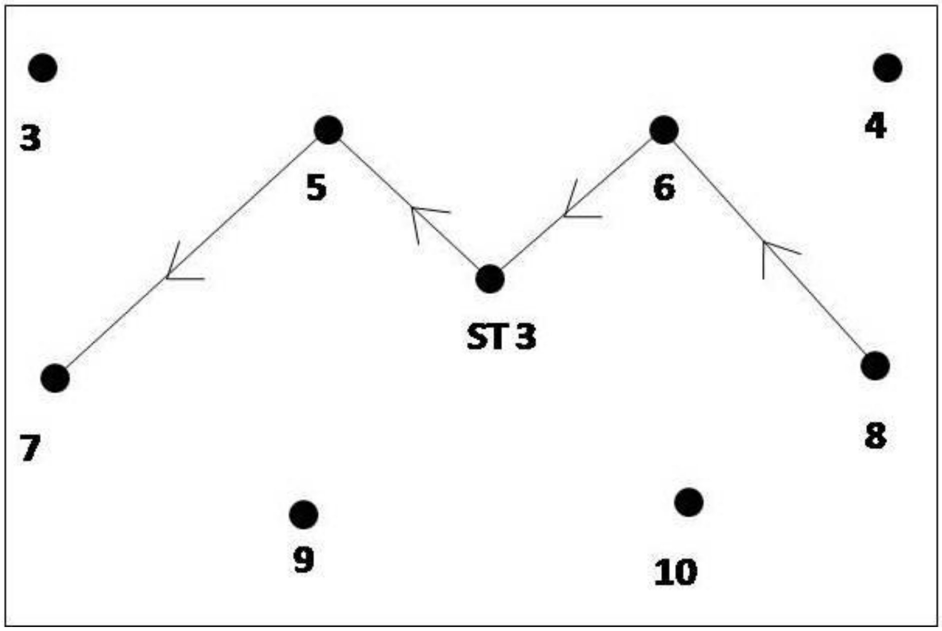



**Figure 4.4 Path for Dynamic Experiments**

The zigzag path consisted of 4 line segments as shown. The line segment from station point 8 to station point 6 was divided by 12 intermediate points. Similarly second, third and last line segment was divided by 9, 10 and 14 points respectively. The coordinates of these points were found out using basic formulae of trigonometry. The path was chosen to be zigzag to keep the path slight complex as compared to the straight path. This path also provided a chance to monitor the accuracy as the path suddenly changes at the station points.

## 4.3 TIME AND LEARNING CURVE ANALYSIS

As discussed in the section 2.3Knowledge Gap, it was important to measure man-minutes consumed for the various steps involved in the deployment and setup of the RTLS. The system was deployed for various times. Table 4.2 shows the man-minutes recorded. On one side of the table there are parts or components of deployment while on the other side the table shows the man-minutes taken in completing that part in various attempts of RTLS deployment. The components or parts in deployment of the system include Bipods placement which were used for surveying purpose. This placement also included centering and leveling of these bipods. Afterwards these bipods were adjusted at a particular height as desired. Finally, a target was placed on the top. The purpose of the target was to determine the position of the control points using the laser scanner.

Sensor stands placement included placement of the stands which supported holding of the sensors. The stands were folded type stands which were unfolded at the site and the sensors were fixed in these stands using the screws. Rest of the terms are already discussed in the section3.4 Experimental Setups.

**Table 4.2 Man-minutes Recorded for Various Steps**

| Deployment Number / Component of Deployment | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Bipods Placement | 15 | 10 | 10 | 10 | 10 |
| Sensors Stands Placement | 15 | 15 | 10 | 15 | 15 |
| Layout & Cabling | 100 | 100 | 40 | 60 | 50 |
| Orientation and Survey | 80 | 60 | 80 | 80 | 60 |
| System Calibration | 90 | 40 | 60 | 20 | 40 |
| **Cumulative Time (man-mins)** | 300 | 225 | 200 | 185 | 175 |

Figure 4.5 shows cumulative time plot for the deployment of the RTLS system in 5 steps already discussed above for 5 times. The purpose of the plot is to observe the learning effect for the deployment of the RTLS. Y-axis on the Figure 4.5shows the man-minutes consumed while the x-axis shows 5 steps which were part of the deployment. 5 curves are plotted showing the deployment of the system for 5 times. It can be seen that as repetition of the system deployment occurs, difference in cumulative time decreases.

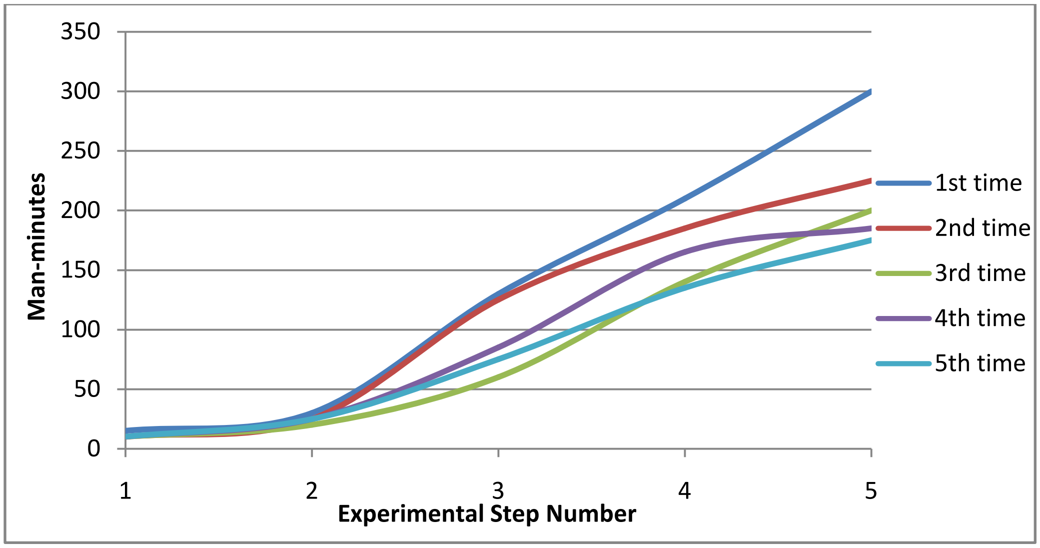



**Figure 4.5 Cumulative Man-minutes for Various Steps**

Figure 4.6 shows the learning curve effect which can be observed. Total man-minutes consumed for the deployment started with 300 man-minutes and became stable after 4 repetitions with time of around 175 man-minutes.

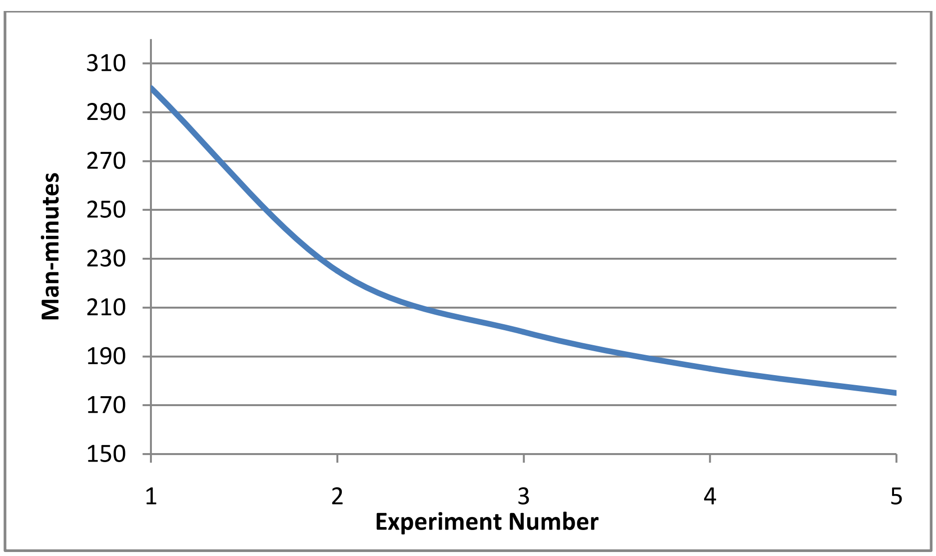



**Figure 4.6 Learning Curve for the System Deployment**

## 4.4 ORIENTATION OF THE SENSORS

As discussed in the section Cell Configuration, three setups were arranged to investigate the accuracy of the RTLS for various configurations. Figure 4.7, Figure 4.8 and Figure 4.9 shows the actual RTLS configuration for full site access, partial site access and offsite setup. These figures show the actual positioning of the sensors relative to the station points. Further these figures show the orientation of the sensors depicting the positioning of their faces to collect data from the site. In addition to the things discussed above, the filled arcs initiating from the sensors show the coverage provided by each of the sensor. For ease the range of each of the sensor is considered to be 35m which may differ from the actual range of the sensors. It is important to note that better coverage is available where a place is covered by the multiple sensors. The dark color in the center as compared to the sides of the site is illustrating the same concept.

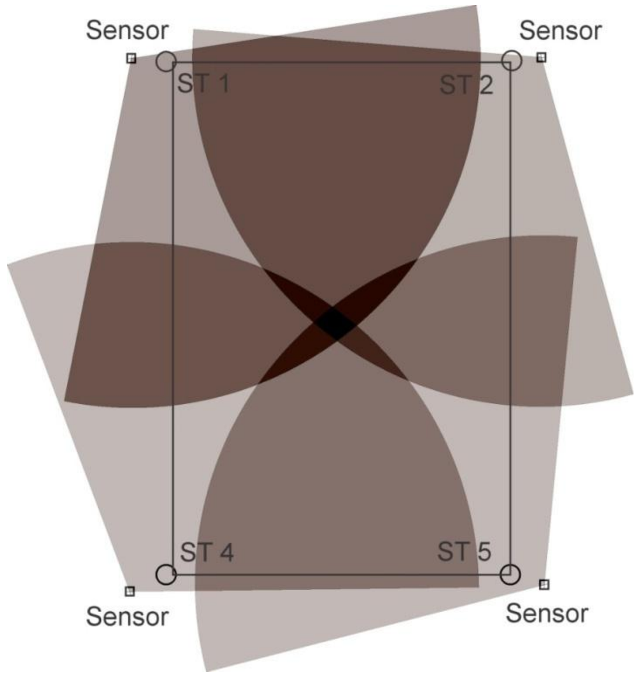



**Figure 4.7 Full Site Configuration**

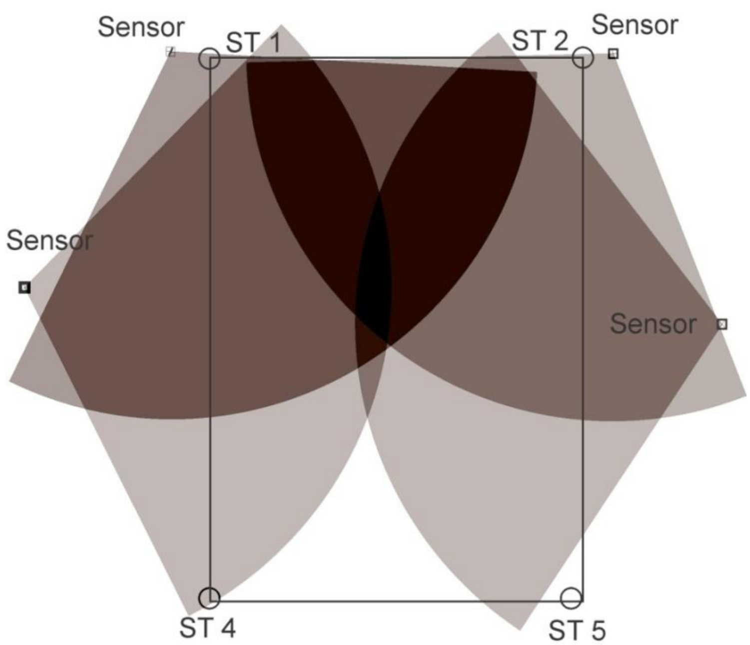



**Figure 4.8 Partial Site Access Configuration**

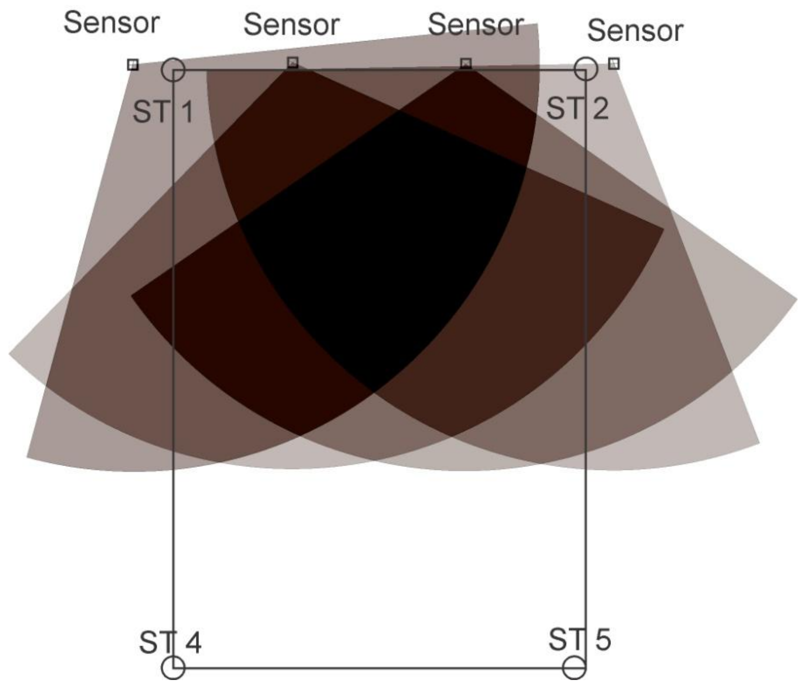



**Figure 4.9 Offsite Setup Configuration**

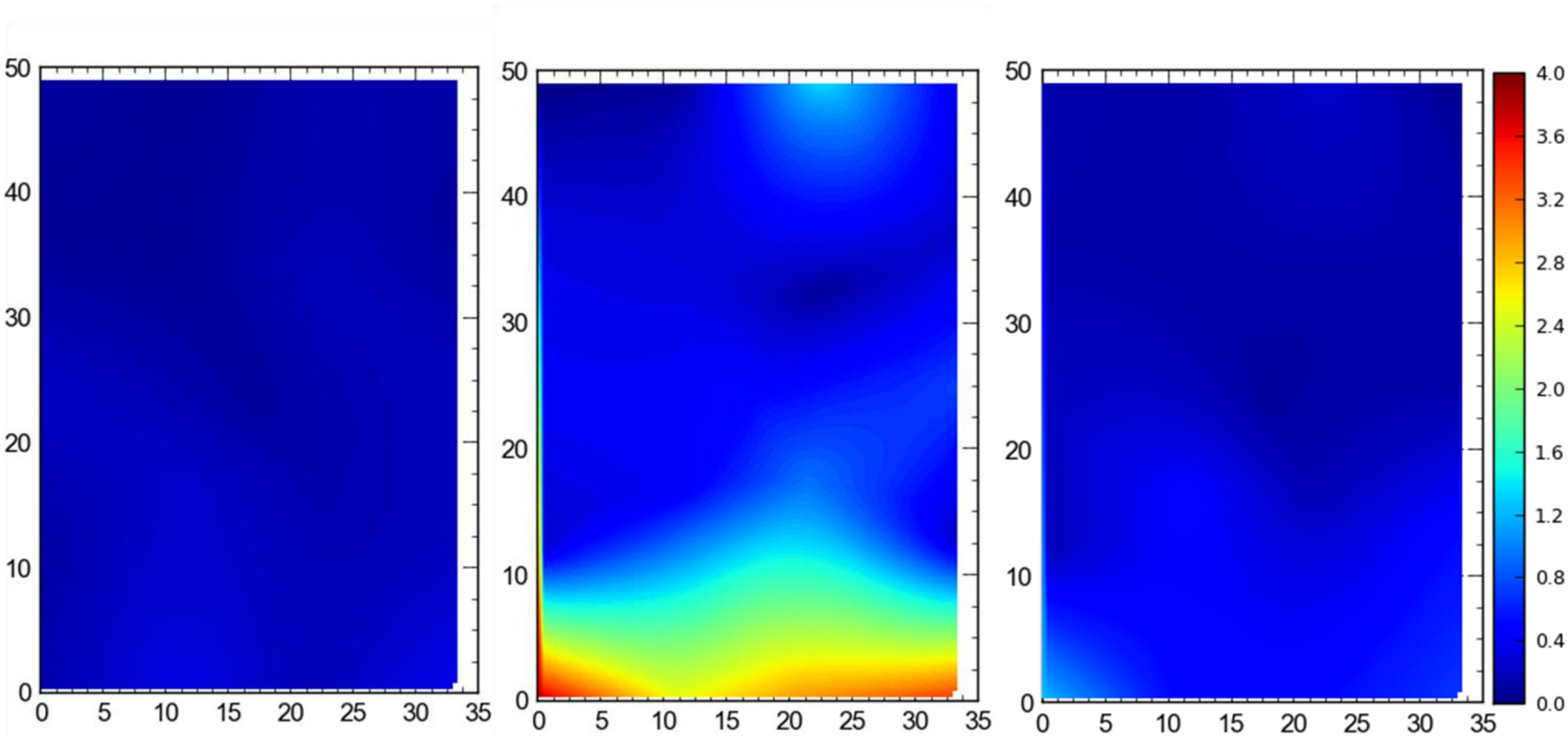
## 4.5 RESULTS FOR STATIC EXPERIMENTS

### 4.5.1 ACCURACY ASSESSMENT FOR SINGLE TAG DEPLOYED

Table 4.3 shows the 2D average accuracy (DRMS) at the station points when a single tag was placed at all station points one by one. As seen in the table, average accuracy for the single tag deployed at all station points was 18cm, 102cm and 32cm for full site access, offsite setup and partial access respectively. The data was collected when the system was also using TDOA for the localization purpose. Figure 4.10 depicts the heat map for average accuracy at various station points all over the test site.

**Table 4.3 2D Average Accuracy Data for the Single Tag Deployed at all Station Points**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.07 | 0.10 | 0.13 |
| **2** | 0.16 | 1.41 | 0.28 |
| **3** | 0.07 | 0.35 | 0.15 |
| **4** | 0.10 | 0.25 | 0.15 |
| **5** | 0.08 | 0.34 | 0.15 |
| **6** | 0.21 | 0.09 | 0.13 |
| **7** | 0.24 | 0.43 | 0.22 |
| **8** | 0.21 | 0.74 | 0.14 |
| **9** | 0.26 | 0.42 | 0.49 |
| **10** | 0.16 | 0.97 | 0.18 |
| **11** | 0.13 | 0.27 | 0.20 |
| **12** | 0.21 | 0.21 | 0.55 |
| **13** | 0.35 | 2.57 | 0.47 |
| **14** | 0.19 | 3.02 | 0.50 |
| **ST-01** | 0.12 | 0.03 | 0.16 |
| **ST-02** | 0.16 | 0.37 | 0.05 |
| **ST-03** | 0.10 | 0.50 | 0.09 |
| **ST-04** | 0.16 | 3.80 | 1.24 |
| **ST-05** | 0.39 | 3.48 | 0.71 |
| **avg. accuracy (m)** | 0.18 | 1.02 | 0.32 |



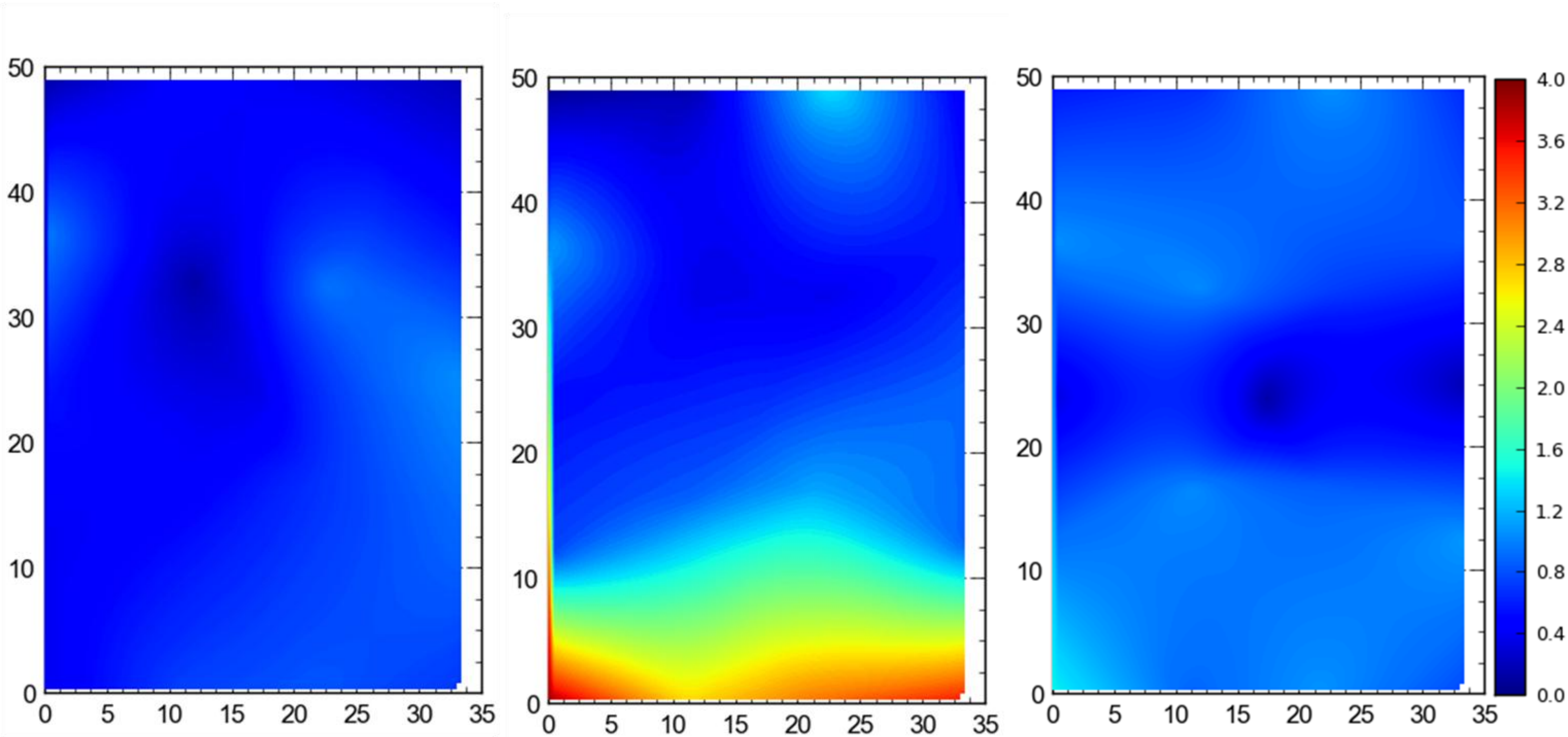

a) Full Site Access b) Offsite Setup c) Partial Access

**Figure 4.10 Heat Map for the Single Tag Deployed at all Station Points (2D)**

Table 4.4 shows the 95$^{th}$ percentile accuracy (DRMS) data for the different configurations when a tag was placed at all station points one by one. Average accuracy was recorded to be 57 cm, 124cm and 82 cm for full site access, offsite setup and partial access respectively. Figure 4.11 illustrates the heat map for the experiment performed.

**Table 4.4 95$^{th}$ Percentile Data for the Single Tag Deployed at all Station Points (2D)**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.50 | 0.18 | 0.68 |
| **2** | 0.35 | 1.42 | 1.09 |
| **3** | 0.98 | 1.11 | 1.07 |
| **4** | 0.54 | 0.56 | 0.83 |
| **5** | 0.13 | 0.36 | 1.04 |
| **6** | 0.95 | 0.38 | 0.73 |
| **7** | 0.56 | 0.51 | 0.33 |
| **8** | 1.06 | 0.90 | 0.19 |
| **9** | 0.46 | 0.86 | 1.05 |
| **10** | 0.68 | 1.17 | 0.86 |
| **11** | 0.40 | 0.78 | 0.97 |
| **12** | 0.90 | 0.90 | 1.10 |
| **13** | 0.76 | 2.74 | 0.88 |
| **14** | 0.83 | 3.16 | 1.08 |
| **ST-01** | 0.13 | 0.05 | 0.58 |
| **ST-02** | 0.19 | 0.40 | 0.66 |
| **ST-03** | 0.37 | 0.69 | 0.12 |
| **ST-04** | 0.40 | 3.90 | 1.47 |
| **ST-05** | 0.71 | 3.58 | 0.78 |
| **avg. accuracy (m)** | 0.57 | 1.24 | 0.82 |




a) Full Site Access

b) Offsite Setup

c) Partial Access

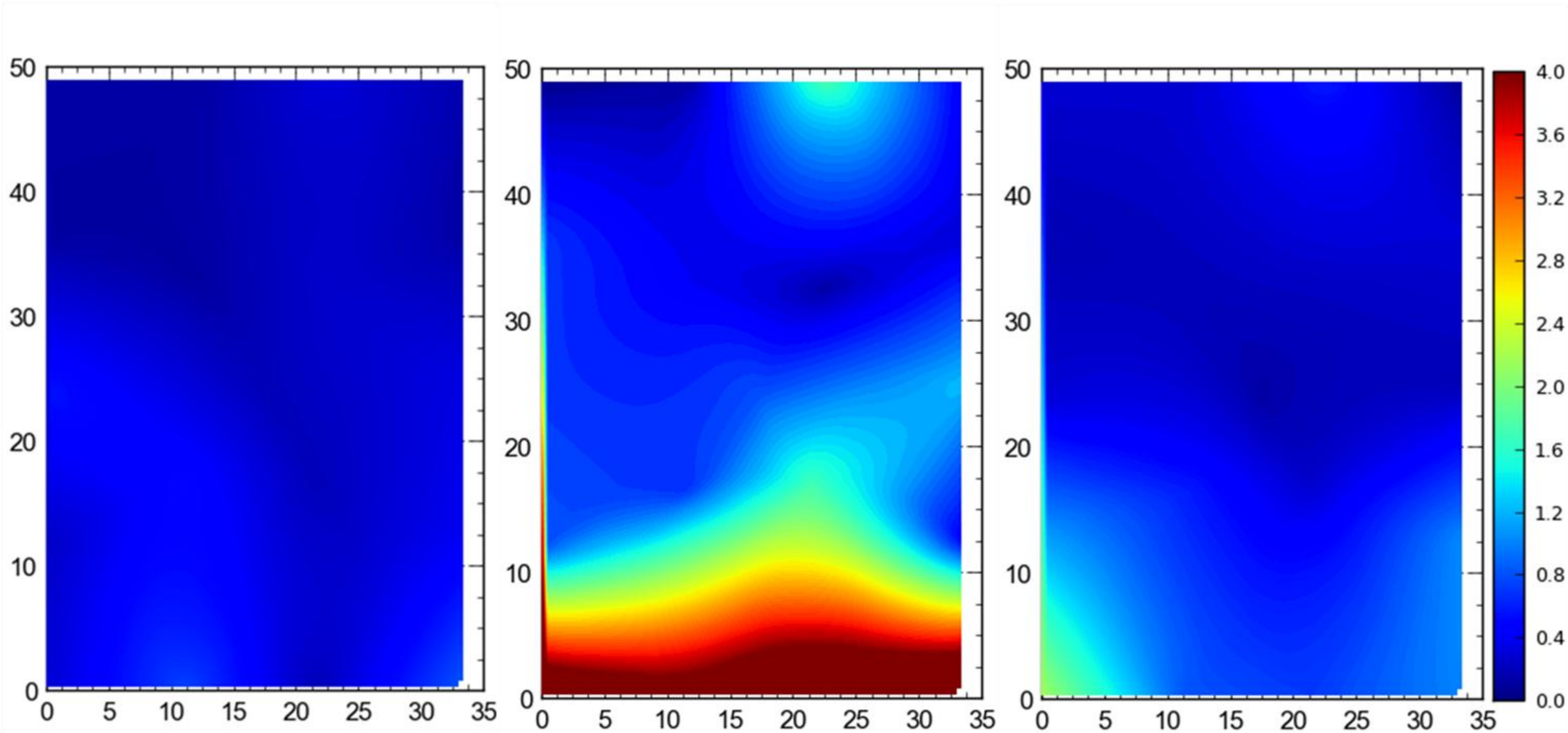


**Figure 4.11 95th Percentile Heat Map for the Single Tag Deployed at all Station Points (2D)**

Table 4.5 shows the average accuracy (MRSE) in 3D for differcent configurations of the sensors of the RTLS. Figure 4.12 demonstrates the heat map for the experiment. Average accuracy was recorded to be 32cm for full site access, 158cm for offsite setup and 56 cm for partial access.

**Table 4.5 3D Average Accuracy Data for the Single Tag Deployed at all Station Points**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.13 | 0.12 | 0.29 |
| **2** | 0.32 | 1.80 | 0.60 |
| **3** | 0.12 | 0.69 | 0.18 |
| **4** | 0.13 | 0.30 | 0.31 |
| **5** | 0.12 | 0.42 | 0.21 |
| **6** | 0.27 | 0.13 | 0.23 |
| **7** | 0.56 | 0.70 | 0.30 |
| **8** | 0.35 | 1.24 | 0.19 |
| **9** | 0.52 | 0.67 | 0.61 |
| **10** | 0.20 | 1.73 | 0.28 |
| **11** | 0.25 | 0.83 | 1.18 |
| **12** | 0.41 | 0.41 | 1.06 |
| **13** | 0.77 | 4.41 | 0.83 |
| **14** | 0.19 | 4.95 | 0.73 |
| **ST-01** | 0.14 | 0.04 | 0.30 |
| **ST-02** | 0.17 | 0.44 | 0.09 |
| **ST-03** | 0.20 | 0.83 | 0.13 |
| **ST-04** | 0.30 | 4.88 | 2.19 |
| **ST-05** | 0.85 | 5.49 | 1.02 |
| **avg. accuracy (m)** | 0.32 | 1.58 | 0.56 |



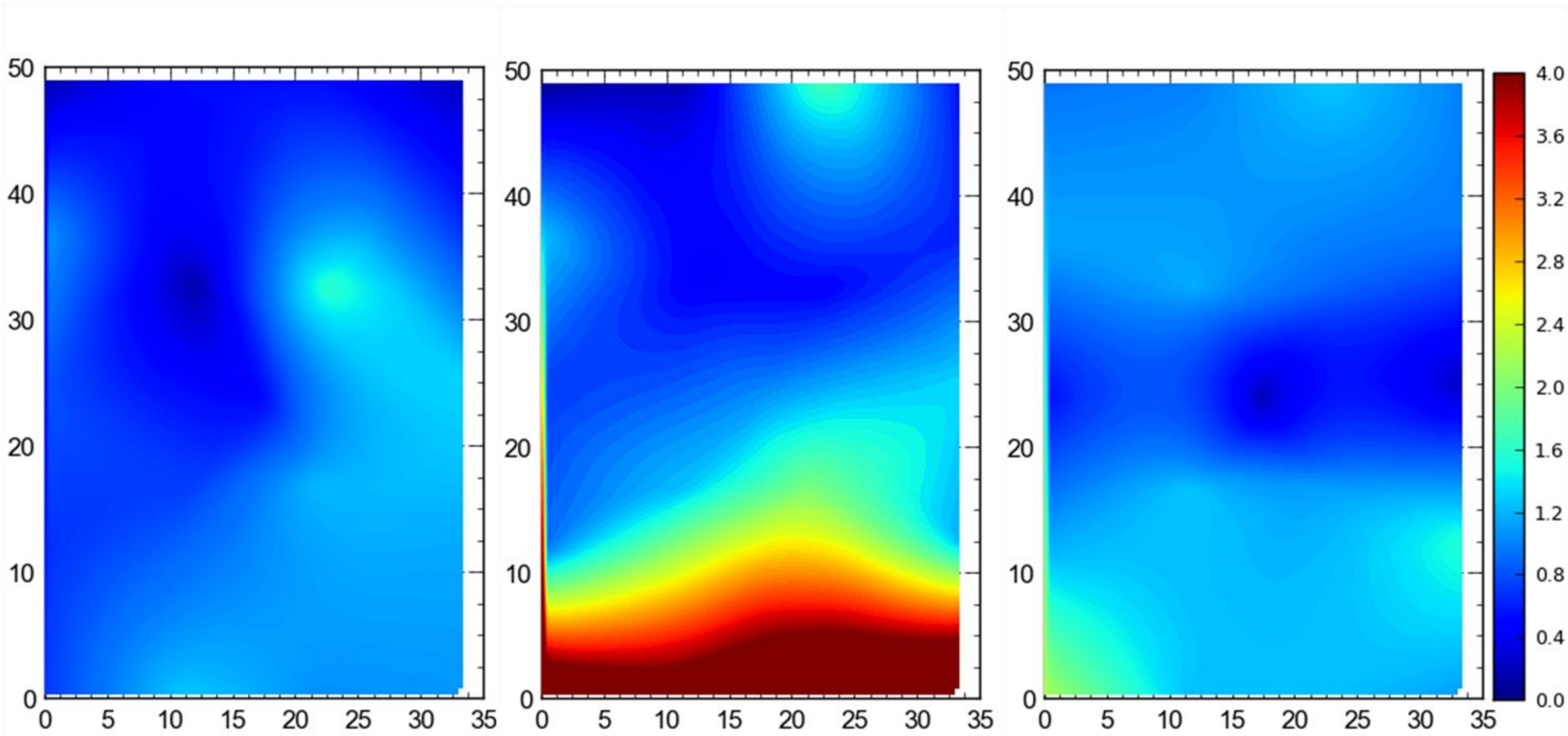

a) Full Site Access b) Offsite Setup c) Partial Access

**Figure 4.12 Heat Map for the Single Tag Deployed at all Station Points (3D)**

Table 4.6 shows the 95$^{th}$ percentile 3D accuracy (MRSE) data for the single tag deployed at all points. For full site access 82cm was the average accuracy for all of the station points while for offsite setup and partial access the average accuracy was measured to be 181cm and 108cm respectively.  Figure 4.13 represents this tabular data in form of heat map.

**Table 4.6 95th Percentile Data for the Single Tag Deployed at all Station Points (3D)**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.55 | 0.20 | 1.00 |
| **2** | 0.49 | 1.80 | 1.30 |
| **3** | 1.09 | 1.26 | 1.15 |
| **4** | 0.68 | 0.62 | 0.97 |
| **5** | 0.16 | 0.44 | 1.18 |
| **6** | 1.62 | 0.47 | 0.90 |
| **7** | 0.81 | 0.71 | 0.54 |
| **8** | 1.34 | 1.36 | 0.23 |
| **9** | 0.74 | 1.28 | 1.28 |
| **10** | 1.22 | 1.99 | 1.12 |
| **11** | 0.69 | 0.94 | 1.19 |
| **12** | 1.17 | 1.17 | 1.57 |
| **13** | 1.30 | 4.51 | 1.27 |
| **14** | 1.07 | 5.14 | 1.27 |
| **ST-01** | 0.15 | 0.07 | 0.95 |
| **ST-02** | 0.21 | 0.54 | 1.01 |
| **ST-03** | 0.51 | 1.07 | 0.18 |
| **ST-04** | 0.73 | 5.01 | 2.23 |
| **ST-05** | 1.09 | 5.76 | 1.11 |
| **avg. accuracy (m)** | 0.82 | 1.81 | 1.08 |




a) Full Site Access b) Offsite Setup c) Partial Access

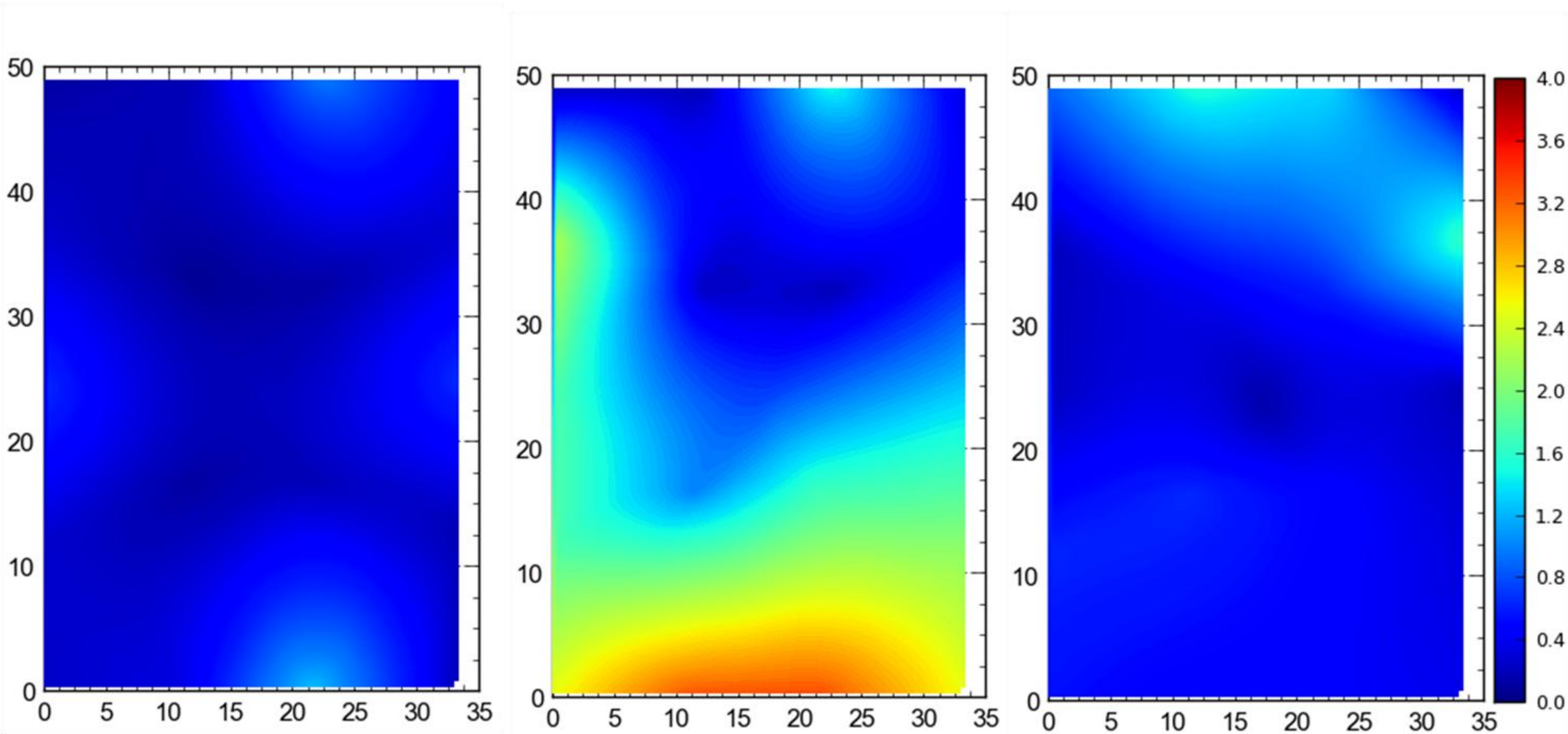
**Figure 4.13 95th Percentile Heat Map for the Single Tag Deployed at all Station Points (3D)**

### 4.5.2 ACCURACY ASSESSMENT FOR THE TAGS DEPLOYED AT ALL POINTS SIMULTANEOUSLY

Table 4.7shows the average accuracy (DRMS) for 2D when all of the station points were occupied with the tags simultaneously. Accuracy dropped as compared to the single tag deployed at all points. Average accuracy was noted to be 38cm, 144cm and 60cm for the three configurations. Figure 4.14 represents this data in form of heat map.

**Table 4.7 2D Average Accuracy Data for Tags Deployed at all Station Points Simultaneously**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.20 | 0.18 | 1.57 |
| **2** | 1.00 | 1.54 | 1.35 |
| **3** | 0.28 | 2.27 | 0.22 |
| **4** | 0.28 | 0.44 | 1.67 |
| **5** | 0.07 | 0.25 | 0.40 |
| **6** | 0.12 | 0.20 | 0.62 |
| **7** | 0.66 | 1.77 | 0.24 |
| **8** | 0.67 | 1.27 | 0.21 |
| **9** | 0.11 | 1.00 | 0.66 |
| **10** | 0.20 | 1.66 | 0.50 |
| **11** | 0.28 | 1.77 | 0.64 |
| **12** | 0.19 | 2.06 | 0.33 |
| **13** | 0.35 | 3.33 | 0.45 |
| **14** | 1.26 | 3.32 | 0.45 |
| **ST-01** | 0.12 | 0.16 | 0.89 |
| **ST-02** | 0.43 | 0.30 | 0.16 |
| **ST-03** | 0.23 | 0.78 | 0.13 |
| **ST-04** | 0.26 | 2.55 | 0.54 |
| **ST-05** | 0.21 | 2.55 | 0.39 |
| **avg. accuracy (m)** | 0.38 | 1.44 | 0.60 |



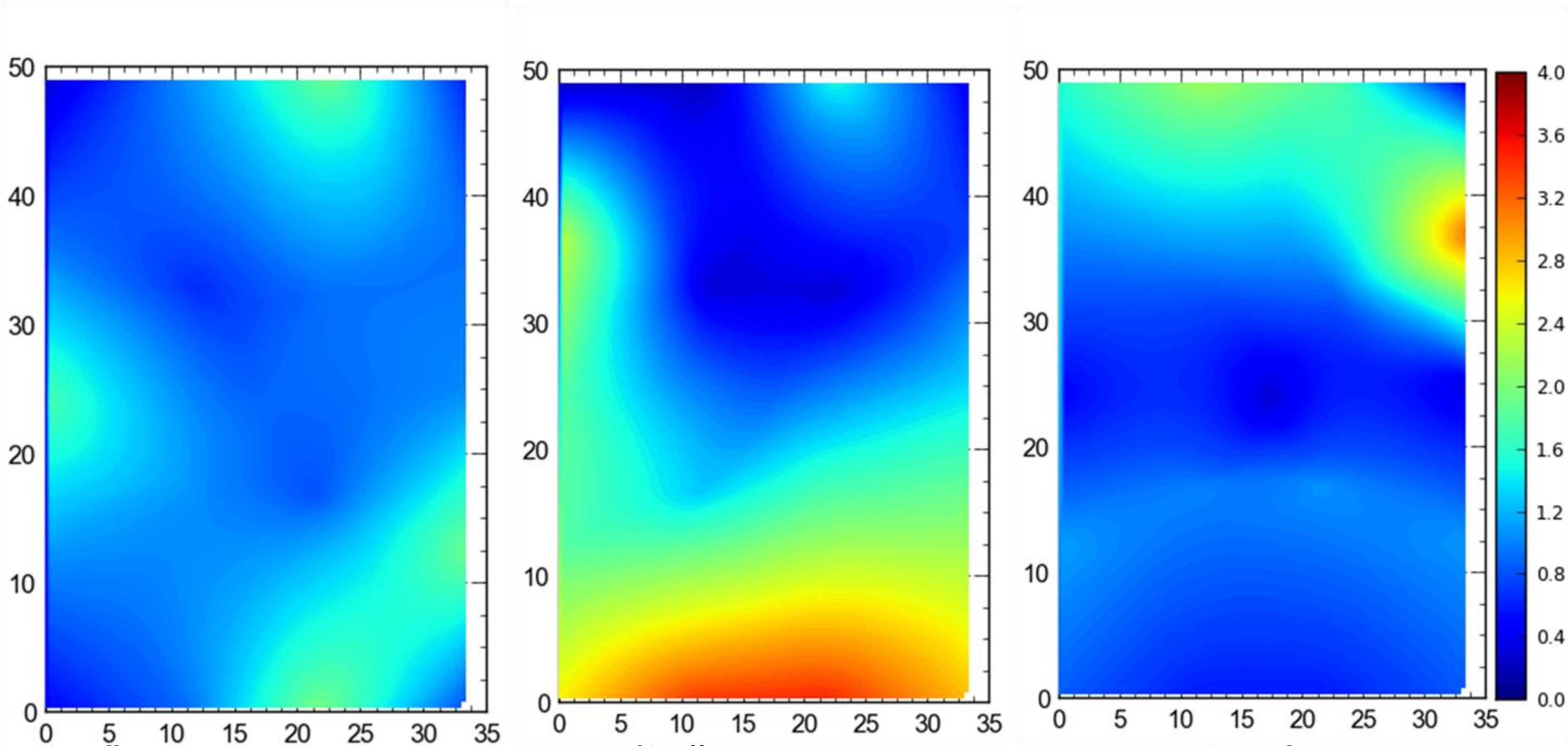

a) Full Site Access b) Offsite Setup c) Partial Access

**Figure 4.14Heat Map for the Tags Deployed at all Station Points simultaneously (2D)**

Table 4.8 depicts the accuracy data (DRMS) for 95th percentile 2D data when all of the station points were occupied with the tags. Average accuracy for 95th percentile was 111cm for full site access, 155cm for offsite setup and 106cm for partial access. Figure 4.15 shows the heat map for this experiment.

**Table 4.8 95th Percentile Data for Tags Deployed at all Station Points simultaneously (2D)**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 1.11 | 0.20 | 2.18 |
| **2** | 1.93 | 1.55 | 1.80 |
| **3** | 0.94 | 2.31 | 1.02 |
| **4** | 0.94 | 0.75 | 3.19 |
| **5** | 0.66 | 0.31 | 0.86 |
| **6** | 0.94 | 0.29 | 0.92 |
| **7** | 1.75 | 1.82 | 0.48 |
| **8** | 1.04 | 1.35 | 0.35 |
| **9** | 1.07 | 1.29 | 1.01 |
| **10** | 0.81 | 1.73 | 1.07 |
| **11** | 1.06 | 1.82 | 1.12 |
| **12** | 1.94 | 2.17 | 1.09 |
| **13** | 0.91 | 3.44 | 0.59 |
| **14** | 1.98 | 3.49 | 0.59 |
| **ST-01** | 0.27 | 0.19 | 1.60 |
| **ST-02** | 0.61 | 0.42 | 0.35 |
| **ST-03** | 0.91 | 0.91 | 0.26 |
| **ST-04** | 0.48 | 2.63 | 0.86 |
| **ST-05** | 0.76 | 2.85 | 0.84 |
| **avg. accuracy (m)** | 1.11 | 1.55 | 1.06 |



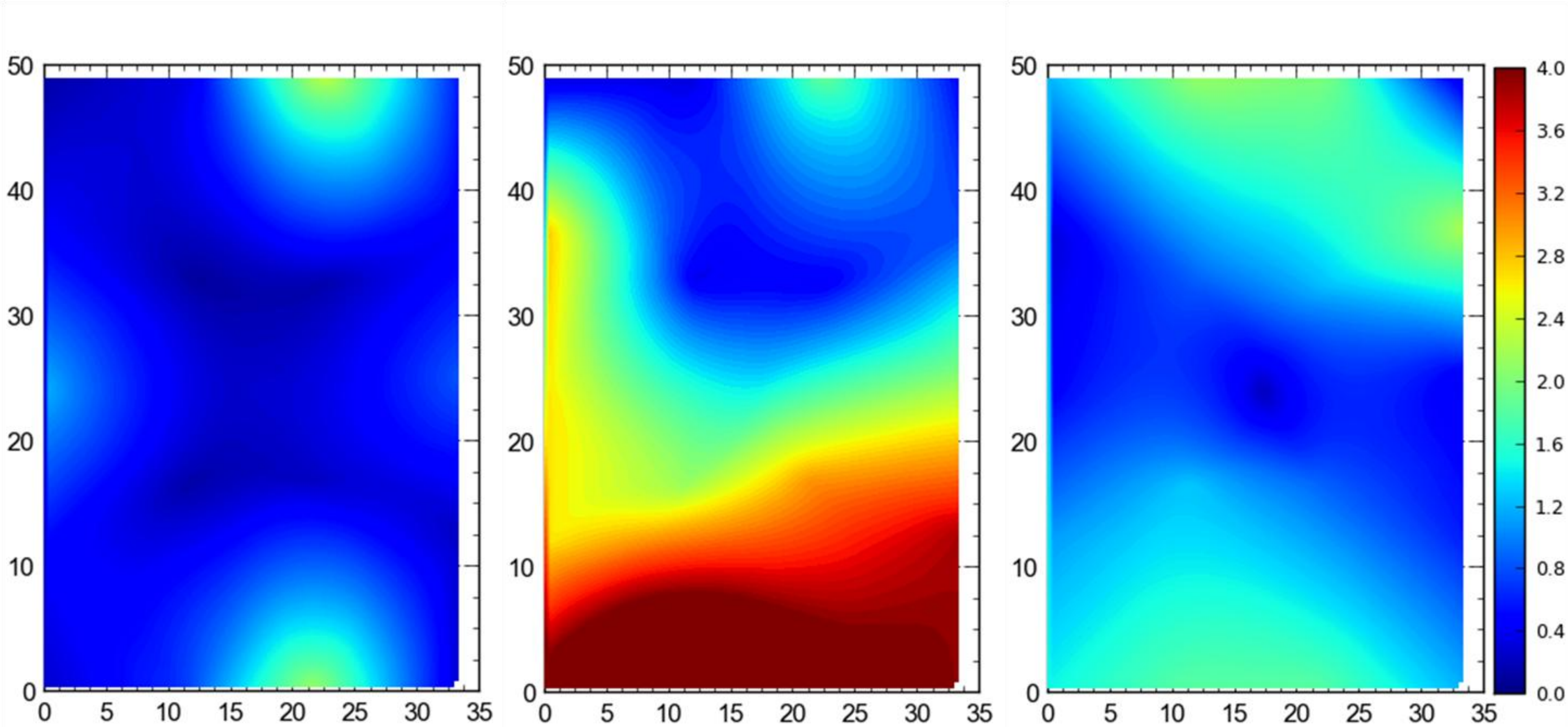

a) Full Site Access b) Offsite Setup c) Partial Access

**Figure 4.15 95% Percentile Heat Map for the Tags Deployed at all Station Points simultaneously (2D)**

**Error! Reference source not found.**shows 3D accuracy data (MRSE) for the scenario hen all of the station points were occupied by the tags simultaneously. Figure 4.16 represents dispersion of accuracy at different station points on the test site. Average accuracy was recorded to be 64cm for full site access, 231cm for offsite setup and 114 cm for partial site access.

**Table 4.9 3D Average Accuracy Data for Tags Deployed at all Station Points Simultaneously**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 0.37 | 0.30 | 2.15 |
| **2** | 2.38 | 1.93 | 1.99 |
| **3** | 0.46 | 2.82 | 0.30 |
| **4** | 0.41 | 0.79 | 2.25 |
| **5** | 0.11 | 0.40 | 0.87 |
| **6** | 0.15 | 0.42 | 1.28 |
| **7** | 1.19 | 2.66 | 0.46 |
| **8** | 0.83 | 2.08 | 0.40 |
| **9** | 0.14 | 2.12 | 1.28 |
| **10** | 0.23 | 3.01 | 0.89 |
| **11** | 0.50 | 2.66 | 1.13 |
| **12** | 0.23 | 3.86 | 0.59 |
| **13** | 0.70 | 6.00 | 1.84 |
| **14** | 2.16 | 4.34 | 1.84 |
| **ST-01** | 0.12 | 0.23 | 1.23 |
| **ST-02** | 0.59 | 0.47 | 0.22 |
| **ST-03** | 0.29 | 1.49 | 0.20 |
| **ST-04** | 0.26 | 4.33 | 1.48 |
| **ST-05** | 0.28 | 3.96 | 1.22 |
| **avg. accuracy (m)** | 0.64 | 2.31 | 1.14 |



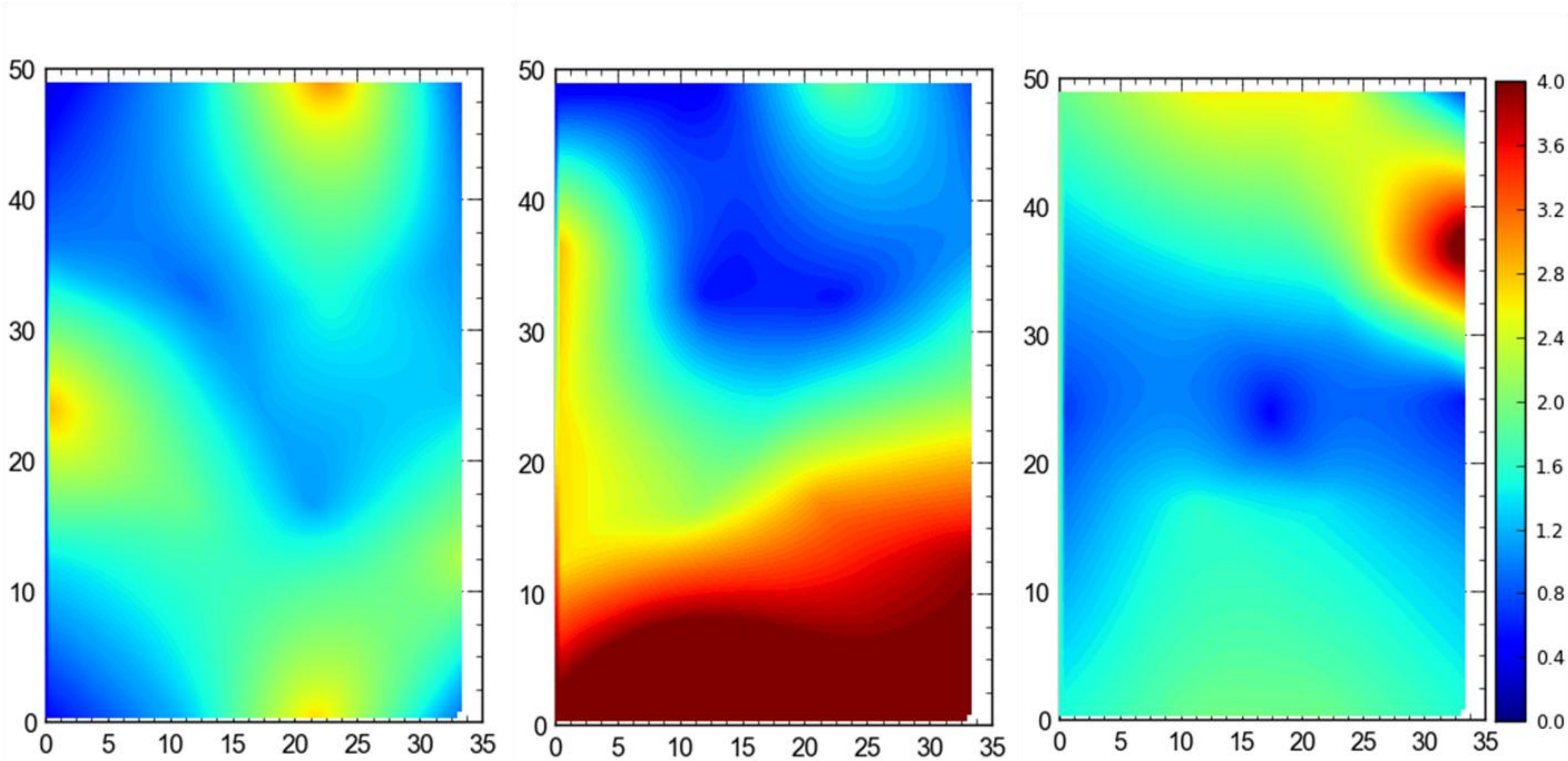

a) Full Site Access b) Offsite Setup c) Partial Access

**Figure 4.16Heat Map for the Tags Deployed at all Station Points Simultaneously (3D)**

Table 4.10 shows the 95$^{th}$ percentile 3D accuracy data (MRSE) for the case when all of the station points were occupied by the tags simultaneously. Figure 4. 17 shows the accuracy distribution in form of heat map. Average accuracy for 95$^{th}$ percentile for full site access, offsite setup and partial access was 151cm, 240cm and 158cm respectively.

**Table 4.10 95$^{th}$ Percentile Data for Tags Deployed at all Station Points simultaneously (3D)**

| Station pt. | Full Site Access | Offsite Setup | Partial Access |
|---|---|---|---|
| **1** | 1.30 | 0.36 | 2.63 |
| **2** | 3.09 | 1.93 | 2.63 |
| **3** | 0.99 | 2.86 | 1.19 |
| **4** | 1.04 | 1.06 | 4.42 |
| **5** | 0.91 | 0.54 | 1.27 |
| **6** | 1.54 | 0.54 | 1.39 |
| **7** | 2.85 | 2.69 | 0.71 |
| **8** | 1.28 | 2.13 | 0.56 |
| **9** | 1.89 | 2.16 | 1.61 |
| **10** | 1.10 | 3.08 | 1.40 |
| **11** | 1.35 | 2.69 | 1.13 |
| **12** | 2.28 | 3.95 | 1.20 |
| **13** | 1.21 | 6.03 | 1.94 |
| **14** | 2.73 | 4.42 | 1.94 |
| **ST-01** | 0.28 | 0.24 | 1.91 |
| **ST-02** | 0.76 | 0.79 | 0.56 |
| **ST-03** | 1.16 | 1.58 | 0.46 |
| **ST-04** | 0.48 | 4.36 | 1.54 |
| **ST-05** | 0.86 | 4.13 | 1.57 |
| **avg. accuracy (m)** | 1.51 | 2.40 | 1.58 |




a) Full Site Access b) Offsite Setup c) Partial Access

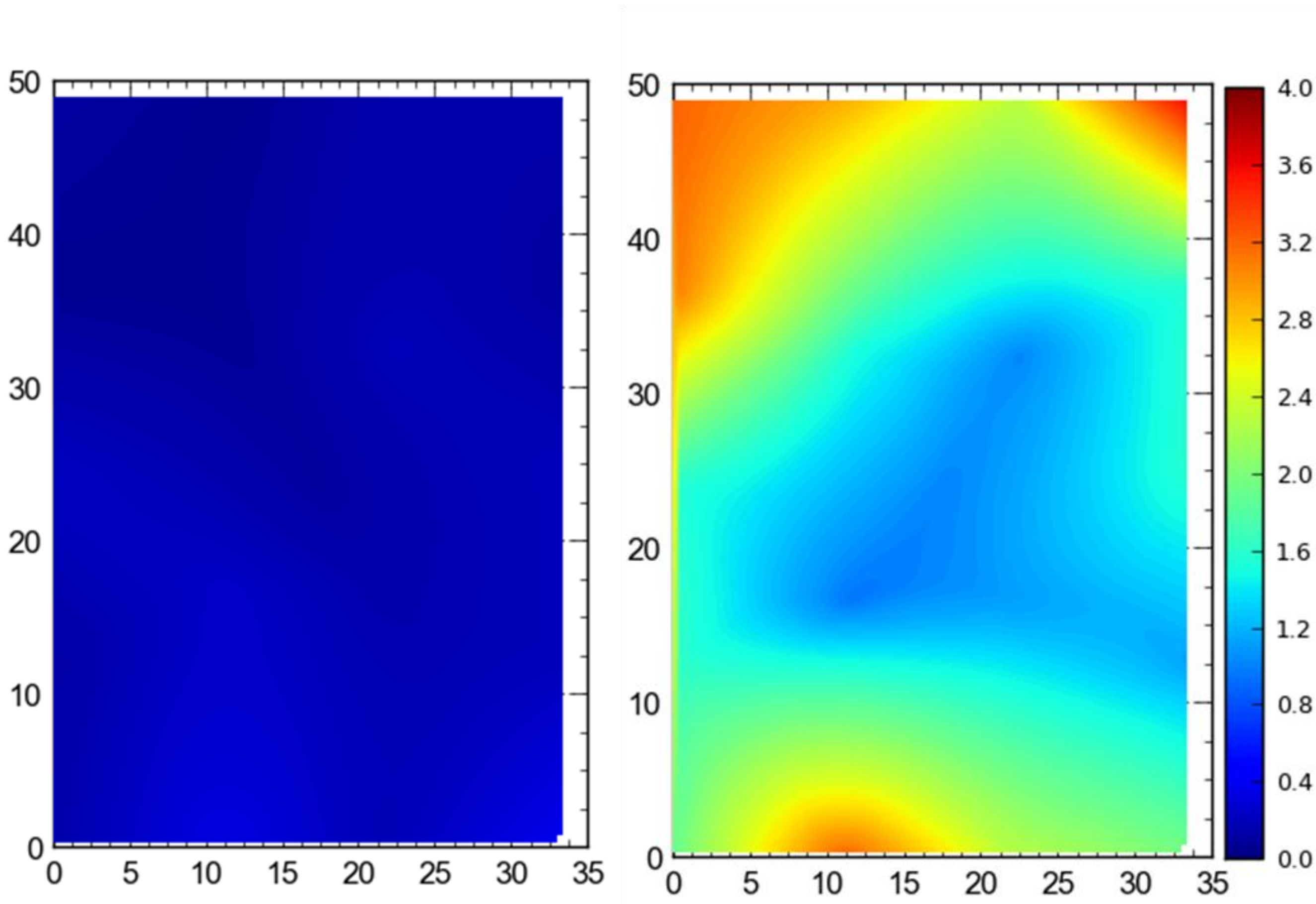
**Figure 4. 17 95th Percentile Heat Map for the Tags Deployed at all Station Points simultaneously (3D)**

### 4.5.3 WITH TDOA VS AOA ONLY EXPERIMENTS

In order to investigate how accuracy in terms of DRMS and MRSE varies when both TDOA and AOA readings are used for localization and when only AOA readings are used, experiments were performed in full site access configuration. Table 4.11 shows difference in accuracy (DRMS) between with TDOA and AOA only. Figure 4.18 shows heat map for the data. For AOA only, the accuracy is relatively good near the center of the site where tags are being tracked by almost all of the sensors.

**Table 4.11 Average Accuracy Data with TDOA vs. AOA Only (2D)**

| Station pt. | with TDOA | AOA only |
|---|---|---|
| **1** | 0.07 | 2.87 |
| **2** | 0.16 | 2.32 |
| **3** | 0.07 | 3.11 |
| **4** | 0.10 | 1.59 |
| **5** | 0.08 | 1.51 |
| **6** | 0.21 | 1.03 |
| **7** | 0.24 | 1.58 |
| **8** | 0.21 | 1.59 |
| **9** | 0.26 | 0.96 |
| **10** | 0.16 | 1.11 |
| **11** | 0.13 | 1.64 |
| **12** | 0.21 | 1.15 |
| **13** | 0.35 | 3.26 |
| **14** | 0.19 | 2.30 |
| **ST-01** | 0.12 | 3.22 |
| **ST-02** | 0.16 | 3.65 |
| **ST-03** | 0.10 | 1.02 |
| **ST-04** | 0.16 | 1.92 |
| **ST-05** | 0.39 | 1.99 |
| **avg. accuracy (m)** | 0.18 | 1.99 |



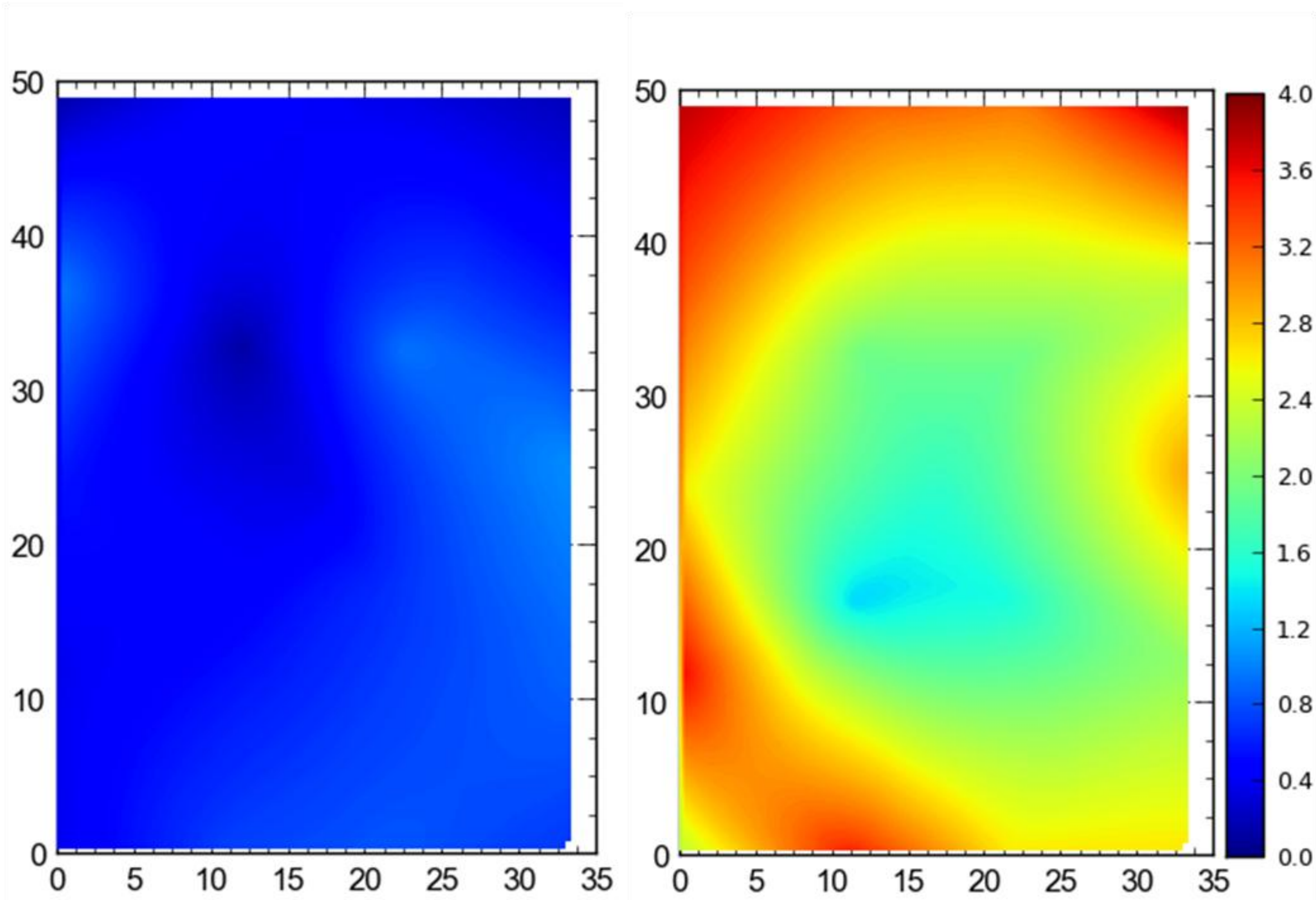

a) with TDOA b) with AOA only

**Figure 4.18 Heat Map Comparison with TDOA vs AOA only (2D)**

Table 4.12 depicts the 3D accuracy difference in terms of MRSE for AOA only versus with TDOA readings. The results are similar to as were in case of 2D results. Figure 4.19 depicts these results in form of heat map. Again the accuracy is better in central region for AOA only readings.

**Table 4.12Average Accuracy Data with TDOA vs. AOA Only (3D)**

| Sr.no | with TDOA | AOA only |
|---|---|---|
| 1 | 0.50 | 3.26 |
| 2 | 0.35 | 3.13 |
| 3 | 0.98 | 3.28 |
| 4 | 0.54 | 2.30 |
| 5 | 0.13 | 1.93 |
| 6 | 0.95 | 1.94 |
| 7 | 0.56 | 2.63 |
| 8 | 1.06 | 2.93 |
| 9 | 0.46 | 1.33 |
| 10 | 0.68 | 1.50 |
| 11 | 0.40 | 3.61 |
| 12 | 0.90 | 2.12 |
| 13 | 0.76 | 3.53 |
| 14 | 0.83 | 2.64 |
| ST-01 | 0.13 | 3.79 |
| ST-02 | 0.19 | 3.91 |
| ST-03 | 0.37 | 1.62 |
| ST-04 | 0.40 | 2.27 |
| ST-05 | 0.71 | 2.67 |
| avg. accuracy | 0.57 | 2.65 |




a) with TDOA b) with AOA only

**Figure 4.19 Heat Map Comparison with TDOA vs. AOA only (3D)**

### 4.5.4 ACCURACY COMPARISON FOR DIFFERENT UPDATE RATES

To find out variation in accuracy as update rate for tag is varied, experiments were performed in partial site access configuration. Table 4.13 shows difference in accuracy (DRMS) for 3 update rates which were 0.87sec, 1.73sec and 3.46 sec. Figure 4.20 shows the heat map for these experiments. From the results it is clear that accuracy increases decreases as update rate decreases.

**Table 4.13 Accuracy Comparison for Different Update Rates (2D)**

| Update Interval / Station pt. | .87 sec | 1.73 sec | 3.46 sec |
|---|---|---|---|
| **1** | 1.58 | 0.06 | 1.57 |
| **2** | 1.32 | 0.78 | 1.35 |
| **3** | 0.29 | 0.21 | 0.22 |
| **4** | 1.77 | 0.51 | 1.67 |
| **5** | 0.97 | 0.27 | 0.40 |
| **6** | 1.09 | 0.32 | 0.62 |
| **7** | 0.68 | 0.17 | 0.24 |
| **8** | 0.60 | 0.07 | 0.21 |
| **9** | 0.95 | 0.46 | 0.66 |
| **10** | 1.12 | 0.31 | 0.50 |
| **11** | 0.73 | 0.87 | 0.64 |
| **12** | 2.45 | 0.47 | 0.33 |
| **13** | 1.68 | 1.67 | 0.45 |
| **14** | 1.59 | 2.30 | 0.45 |
| **ST-01** | 0.93 | 0.14 | 0.89 |
| **ST-02** | 1.06 | 0.25 | 0.16 |
| **ST-03** | 0.26 | 0.13 | 0.13 |
| **ST-04** | 1.20 | 1.27 | 0.54 |
| **ST-05** | 2.02 | 1.39 | 0.39 |
| **avg. accuracy (m)** | 1.17 | 0.61 | 0.60 |

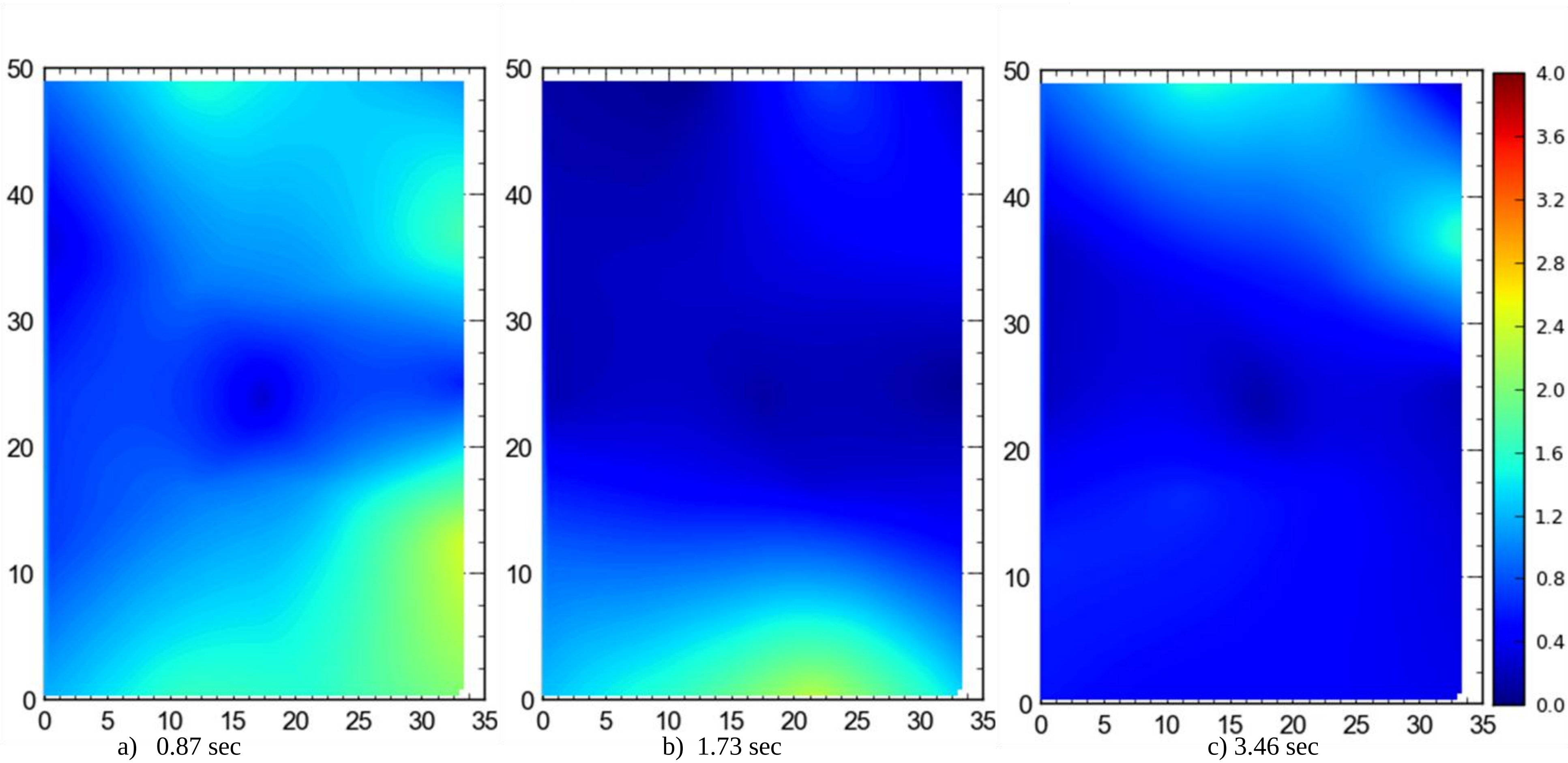
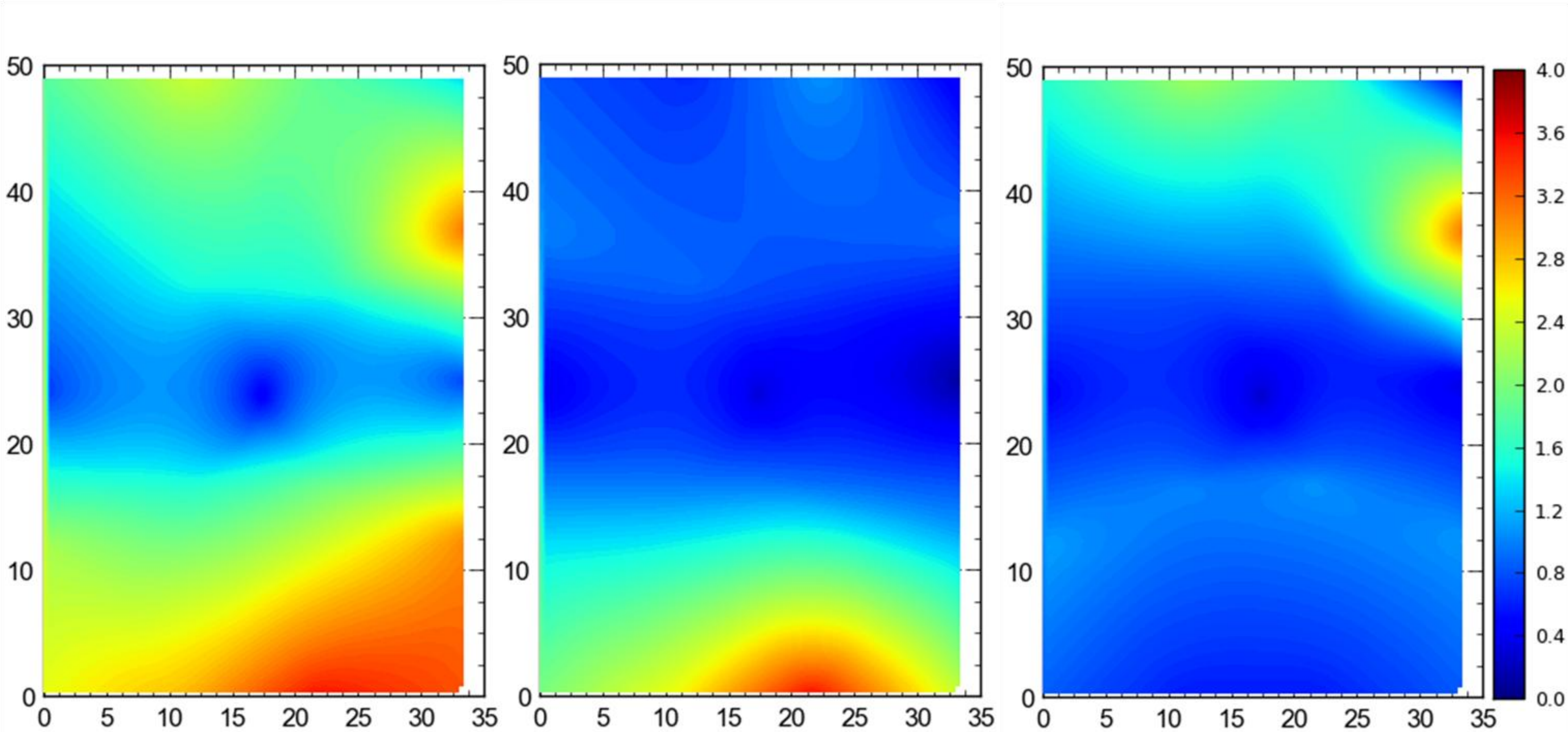



**Figure 4.20 Accuracy Comparison for Different Update Rates (2D)**

Table 4.14 shows difference in accuracy in terms of MRSE as update rate changes for the RTLS. The results are similar to DRMS results. Figure 4.21 shows the heat map for the experiments.

**Table 4.14Accuracy Comparison for Different Update Rates (3D)**

| Station pt. \ Update Interval | .87 sec | 1.73 sec | 3.46 sec |
|---|---|---|---|
| 1 | 2.40 | 0.65 | 2.18 |
| 2 | 1.84 | 1.09 | 1.80 |
| 3 | 1.25 | 1.01 | 1.02 |
| 4 | 3.17 | 0.92 | 3.19 |
| 5 | 1.53 | 0.90 | 0.86 |
| 6 | 1.59 | 0.76 | 0.92 |
| 7 | 0.73 | 0.38 | 0.48 |
| 8 | 0.76 | 0.12 | 0.35 |
| 9 | 1.58 | 1.00 | 1.01 |
| 10 | 1.88 | 0.93 | 1.07 |
| 11 | 2.21 | 1.39 | 1.12 |
| 12 | 3.05 | 1.18 | 1.09 |
| 13 | 2.86 | 2.60 | 0.59 |
| 14 | 3.55 | 3.58 | 0.59 |
| ST-01 | 1.83 | 0.83 | 1.60 |
| ST-02 | 1.29 | 0.39 | 0.35 |
| ST-03 | 0.41 | 0.31 | 0.26 |
| ST-04 | 2.53 | 2.00 | 0.86 |
| ST-05 | 3.30 | 2.38 | 0.84 |
| avg. accuracy (m) | 1.99 | 1.18 | 1.06 |




a) 0.87 sec b) 1.73 sec c) 3.46 sec

**Figure 4.21Accuracy Comparison for Different Update Rates (3D)**

## 4.6 DYNAMIC EXPERIMENTS

Dynamic experiments were performed as mentioned in the section 4.2for all three configurations of the sensors. For full site access the results were relatively the best with average accuracy of 77cm based on DRMS. Visual representation of the experiment is shown in the Figure 4.22. Station points are visible in the figure. Location data is shown in form of red circles as a person carrying the tag walked through the pre-determined path.

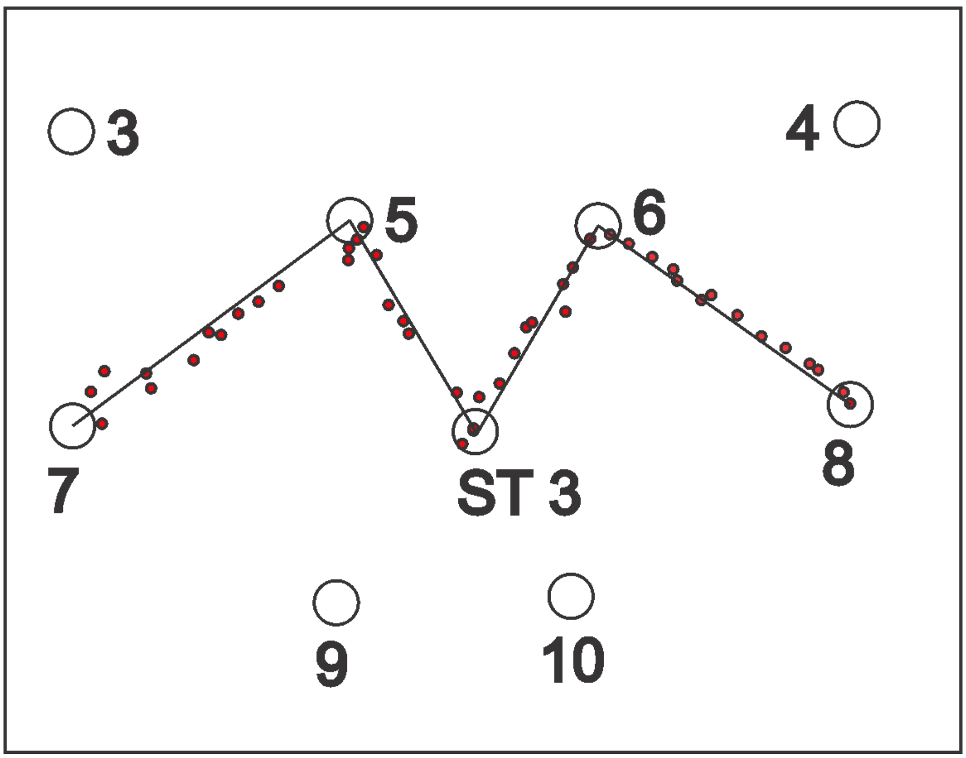



**Figure 4.22 Dynamic Experiment Result for Full Site Access**

Similarly the experiment was repeated for the offsite setup and average accuracy was calculated to be 146cm. Figure 4.23 illustrates the experiment performed for offsite setup.

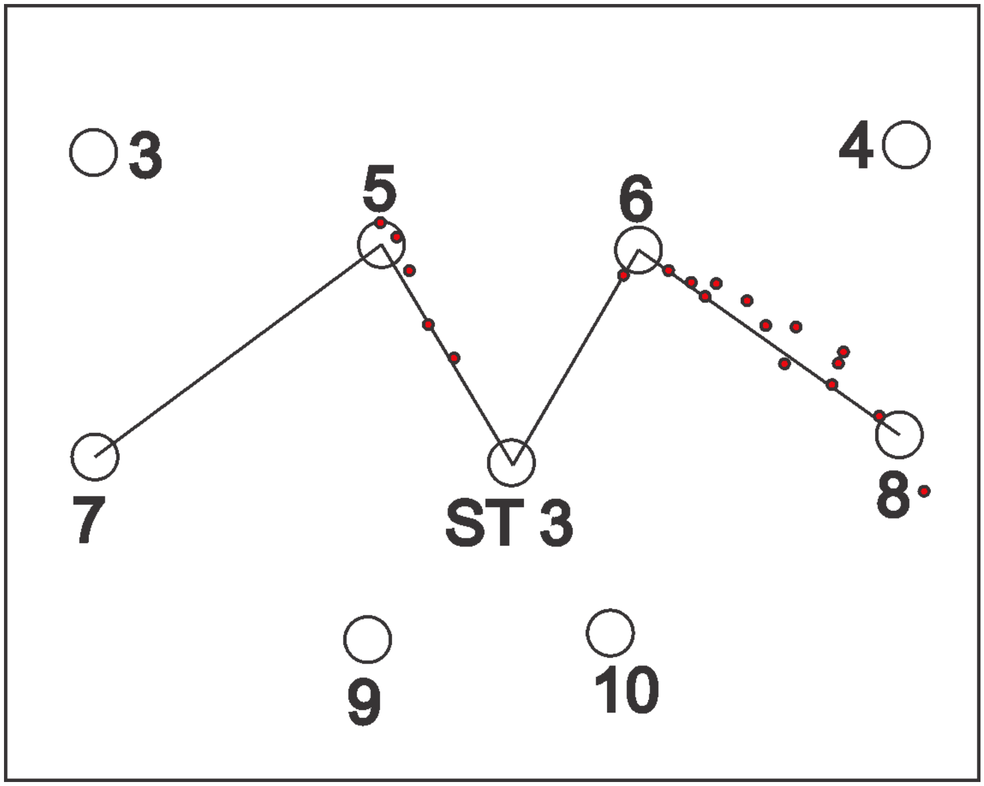



**Figure 4.23 Dynamic Experiment Result for Offsite Setup**

For partial site access the average accuracy was calculated to be 117cm for 2D data. This accuracy was better than offsite setup while less accurate than full site access. Figure 4.24 shows the experiment performed for partial site access.

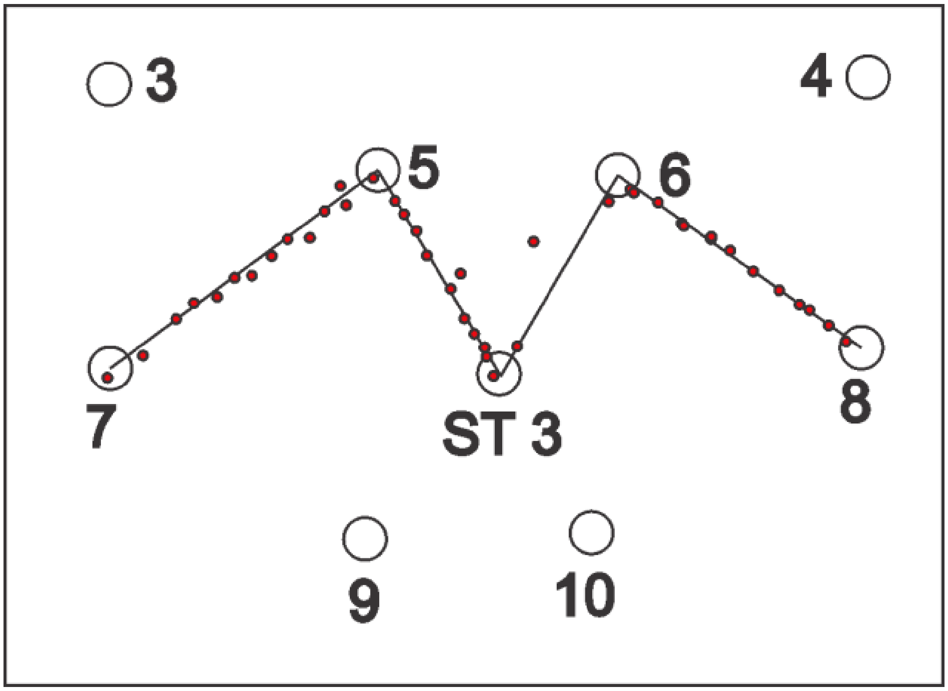



**Figure 4.24 Dynamic Experiment Result for Partial Site Access**

# CHAPTER 5

# DISCUSSION OF RESULTS

## 5.1 DISCUSSION FOR THE STATIC EXPERIMENTS

For static experiments, it can be observed that best average accuracy was obtained using full site access configuration followed by partial access configuration. It is important to note that the average accuracy for a setup is dependent on the configuration of the sensors. The worse average accuracy does imply that a configuration should not be used. Heat maps explain the phenomenon well. For offsite set-up we have observed the worst average accuracy for all of the three scenarios, but this doesn't imply bad performance. For all of the experiments under offsite setup has shown worse performance around the boundary line joining the station points ST-4 and ST-5. If we only consider the average accuracy then we may conclude that this configuration does not provide useful location data but as we see the heat maps, we will come to know that accuracy is much better near the center and the boundary joining the station points ST-1 and ST-2. Such a configuration is handy when we do not have access to the site. Figure 5.1 shows 95$^{th}$ percentile 3D heat map for a tag placed at all points one by one overlaid with the orientation of the sensors for offsite setup. This overlaying explains much better accuracy in the middle than around the boundary line joining the station points ST-4 and ST-5. Nearer the sensors, the accuracy is much better and the systems works best for the area which is covered by multiple sensors. As soon as distance is increased away from the sensors, accuracy starts dropping gradually.

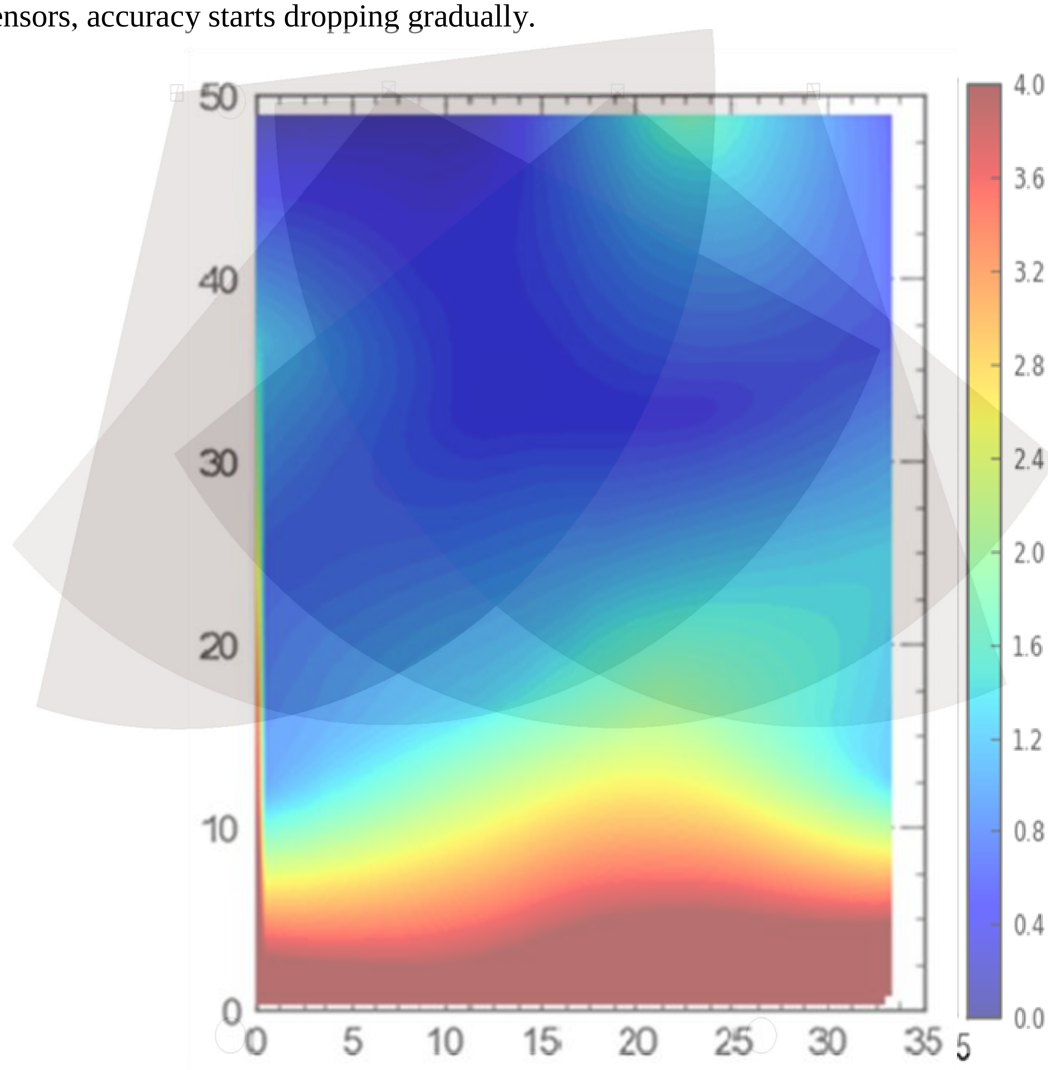



**Figure 5.1 Heat Map Overlaid with Sensors` Orientation (Offsite Setup)**

Previous literature talked about poor accuracy when sensors are not dispersed in both x and y direction. But these experiments performed have shown good results when the objects being tracked are nearer to the sensors (30-35m).

Similarly, for partial site access, much better accuracy is observed in the central region than other parts of the site. Figure 5.2 shows 95$^{th}$ percentile heat map for the single tag deployed at all points for 3D overlaid with the sensors orientation. This overlaid map explains well why the accuracy is much better in the central region than rest of the site. Similarly, it also explains why around the boundary joining station points ST-4 and ST-5 have lesser accuracy as compared to the rest of the site.

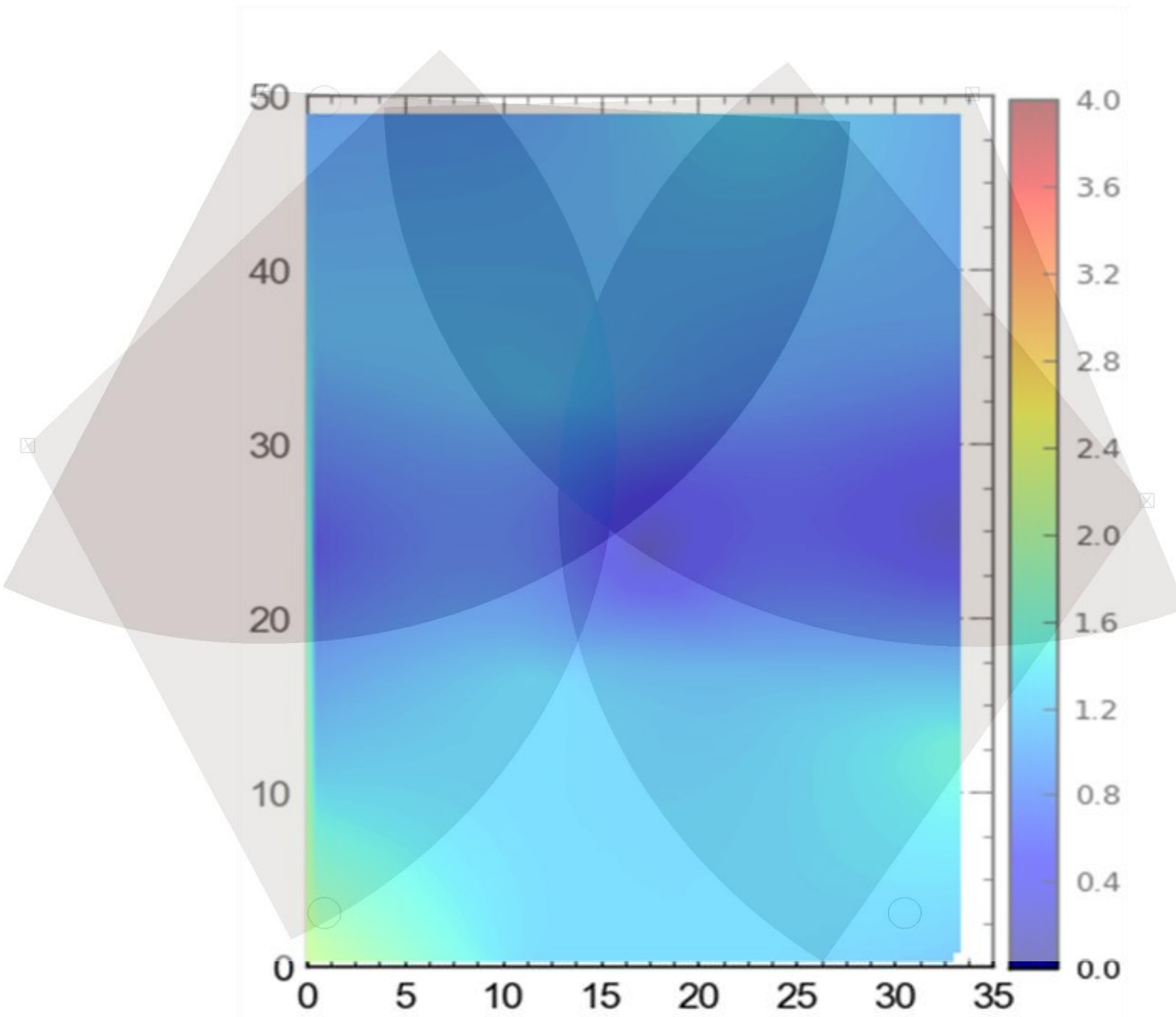



**Figure 5.2 Heat Map Overlaid with Sensors` Oreintation (Partial Access)**

Although full site access configuration has shown much better accuracy but in some cases the accuracy all around the site is not suitable for real time tracking of the resources. For example, AOA-only experiments have shown results not as good as with TDOA experiments. This is because of the fact that input data for localization lessened, causing to estimate location of a resource based on only AOA readings. However in the middle of the site, the resource was being tracked by almost all of the sensors. Figure 5.3 shows heat map for 2D average accuracy for AOA experiment overlaid with the sensors` orientation. This overlaying explains better coverage in the center of the site than rest of the area.

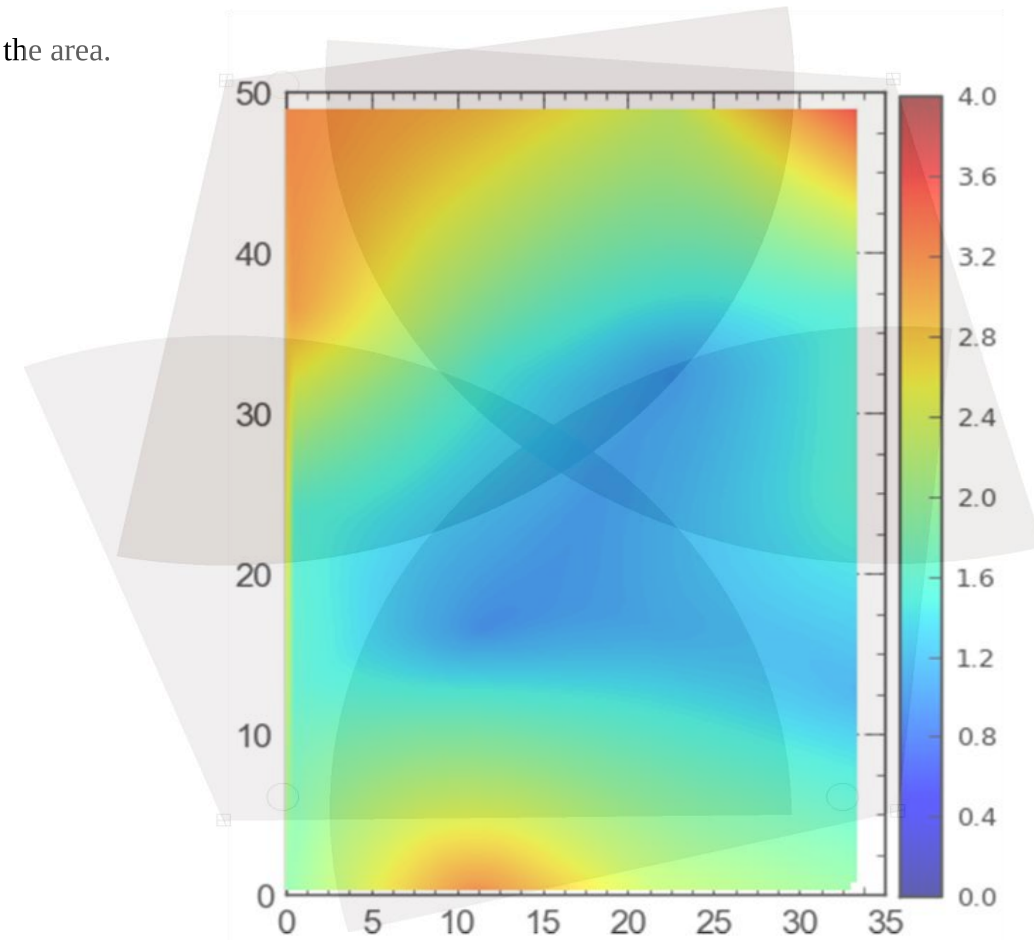



**Figure 5.3 Heat Map Overlaid with Sensors` Orientation (Full Site Access)**

## 5.2 DISCUSSION FOR THE DYNAMIC EXPERIMENTS

Sub-meter accuracy for the full site access configuration and around 1m accuracy for partial site access configuration has shown good results for real time tracking of the construction resources. Offsite setup has shown decreased average accuracy of around 1.5m. However, the problem can be seen that the system has not displayed the location data for the line segment from station points 5 to 7 and 6 to ST-3. Graphical representation of the results of dynamic experiment overlaid with sensors` orientation explains this problem.

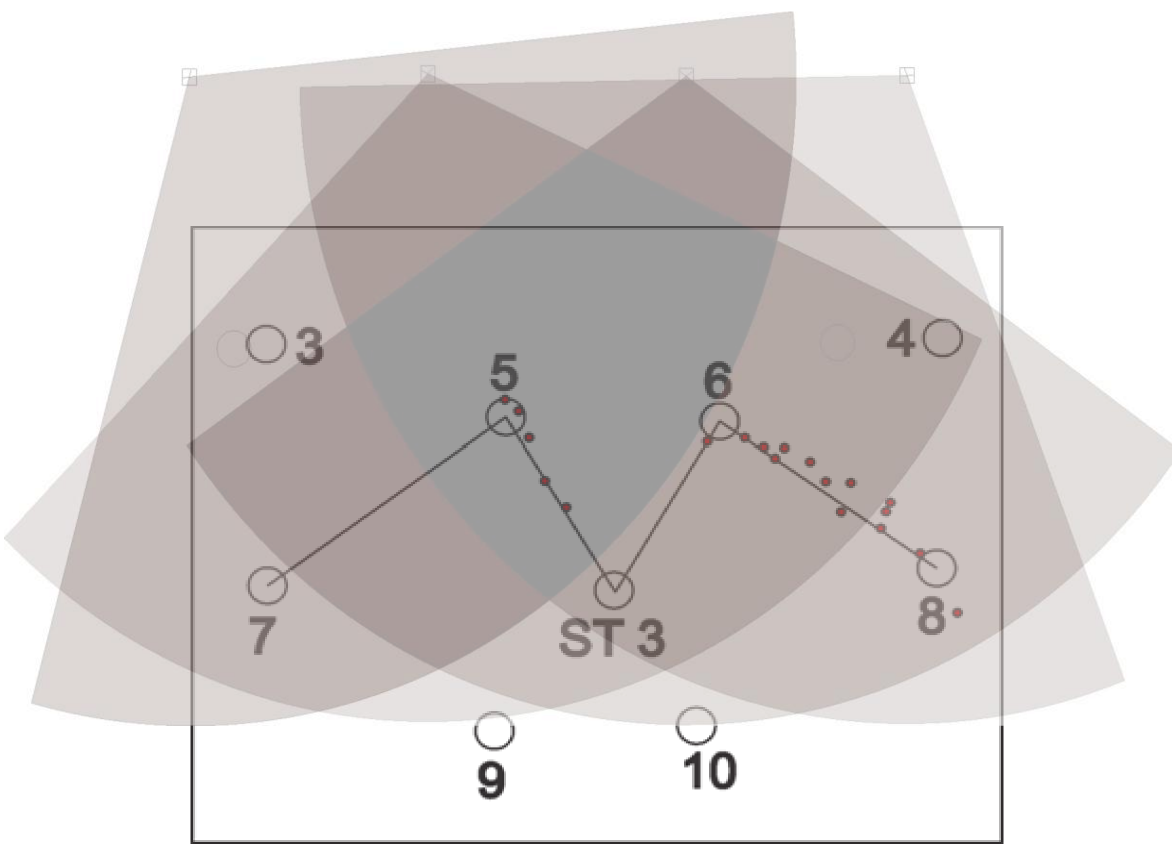



**Figure 5.4 Dynamic Experiment Results Overlaid with Sensors` Orientation (Offsite Setup)**

Figure 5.4 shows the result of dynamic experiments overlaid with the sensors` orientation for offsite setup. When the tag carrier moved from station point 8 to 6, the tag was visible to the sensors. However, when he moved from station point 6 to 3, the tag was not visible to the sensors. It is important to mention that tag was being carried in the hand. Same was the case when the carrier moved from station point 5 to 7. Therefore, we can conclude that while using the RTLS; elevate the tags so that they can be sighted by the sensors without any obstruction.

## 5.3 SAFETY IMPLICATIONS

Cabling is a major safety concern for deployment of the RTLS on the construction sites. Cabling can be minimized by using DC supply for the sensors and using localization techniques, those do not require TDOA signals. Accidents may happen causing damage not only to the system but also to the workers and other staff on the construction site. In order to minimize the risk of the accidents, it is better to do pre-planning of the implementation of the RTLS so that safe cabling can be done on the construction sites. For safe operation, underground cabling may be done as conditions of the construction site allows. If special cases, system can be deployed without cabling using AOA signals only.

Special care must be exercise in deciding the location of the sensors because damage to the sensors will be expensive, repairing may not be locally available, replacement is not easily available and the system may become impaired and of no use. When deploying the sensors on stands, make sure the cabling is done properly, else lugging on the sensors can cause damage to the sensors.

Running wires are hazardous for people on the jobsite and also for the construction machinery. While deploying a real time location system on construction jobsites, risk analysis should be done prior to the deployment.

The sensors are prone to damage when exposed to dust and rain. So weather update should be considered before the deployment. If possible, the sensors should be provided with a cover to protect against rain water. For outdoor operations the system should not be left outside unless under special circumstances.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

Based on the accuracy parameters obtained, man-minutes requirement and hand on experience on the RTLS, we can say that deployment of UWB based RTLS is effective only for some types of construction sites. Since each sensor provide around 35m of effective coverage and coverage from multiple sensors is required for good results. Usually construction sites are bigger than our test area and it is difficult to manage cables and safe area for RTLS. The system is recommended for critical project activities, such as assembling a reactor, girder launching of a flyover, concrete pouring of a critical slab, erection of steel structures e.t.c. For such activities RTLS will prove itself much beneficial.

The RTLS can be deployed on some parts of the construction sites for the activities similar to the above activities. Further it is advisable to use the UWB based RTLS on fabrication yards on construction sites and also for offsite fabrication units where the things are not as much dynamic as on the working construction site. During deployment for such activities, any cell configuration may be used but the equipment or resources to be tracked should be in range of the sensors and multiple sensors should provide coverage to them.

Based on the hand on experience on the RTLS following considerations must be kept in mind while deploying the RTLS.

- Make sure the network cables are in working condition (we once wasted hours in figuring out that what had gone wrong).
- Complete the cabling process before the survey process.
- Deploy the servers outside the boundary of the area which you want to monitor by 5m approximately.
- Make sure that cables will not obstruct the working on the site.
- Cables should not be lugging the sensors (we broke a sensor because we neglected this).
- Make sure that the sensors` stands are standing firm and can absorb vibrations and movements from the winds.
- Keep the user`s manual on the site for troubleshooting.
- Try to bury the cables in the ground to keep the system and site undisturbed
- Keep the height of the sensors as high as possible (greater than 2m).
- Make sure that the direction of the sensors is such that all of the area is being covered by the multiple sensors.
- In case the sensors are deployed on the stands instead of walls, make sure that the site equipment will not hit them.
- Be aware of the falling objects on the site.
- Make a check-list for the tasks which are needed to be performed while deploying the system.
- Turn the tags off after use to conserve the battery usage.
- Double check the data is being recorded for post deployment analysis.

- Adjust the filters and tag update rate based on the need and situation.
- Try to achieve better calibration as it will dictate the accuracy of the system.
- Keep on changing the setup (in term of location and position of the sensors) as the characteristics of the construction site changes during the lifecycle of the project.
- Mock testing is suggested at a small level before deployment at site to make sure that all of the components are working well.
- Tags should be attached to the top of the resources at such a place such that sensors may have direct line of sight.
- Capture the screen of the platform on which you are running the system for educational and help purposes.
- Estimation platform should be established at a place which is separate from main working area.
- Establish benchmarks at such places which can be used effectively throughout the time span during which the system will be deployed.
- Make sure that yaw, pitch and roll of the sensors are adjusted well.
- Image analysis of yaw, pitch and roll is helpful in making sure that entire site is being covered by multiple sensors.
- Introduce the tags one by one in the working area.
- Devise appropriate method to roll the wires.
- Tag the wires according to the deployment needs as this will help in repeated deployment of the system.

- Make sure that enough battery power is available for the surveying equipment and the system.
- Adjust the update rate of the tags before beneficial use.
- Tie the tags to the equipment or assets by appropriate method so that the tags may not fall.

The system was tested on a large scale open site to study the feasibility of the system on the construction site. Although I believe that the work has added value to the domain knowledge but still there is a need to study the system at actual construction jobsites, fabrication yards and hazardous sites for a large scale deployment. Deployment of the system as per recommended protocols by the manufacturer and other researchers on a large site will aid the industry and researchers further more in evaluating the performance of the system for the construction industry.

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# VITAE

## Personal Information

**Name** Waleed Umer

**Father's Name** Muhammad Aslam

**Date of Birth** 20th July 1990

**Nationality** Pakistani

**Residential Address** 22/A Umer Street # 31, Burni Road, GarhiShahu, Lahore, Pakistan

**E-mail Address** waleedumer@hotmail.com

## Educational Qualification

| S.No. | Name of Institution | Degree | Passing Year | CGPA |
|---|---|---|---|---|
| 1. | King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia | M.S. Construction Engineering & Management | November 2014 | **3.81/ 4.0** |
| 2. | University of Engineering & Technology, Lahore, Pakistan | B.E. Civil Engineering | July 2012 | **3.57/ 4.0** |

## Professional Experience

1. **Employer : National Engineering Services Pakistan (NESPAK), Pakistan**

   **Period :** July 2012–January 2013

   **Position :** Junior Engineer (Site Engineer)

   **Projects :** Worked on Metro Bus Project Lahore, Model Town underpass Lahore and Kalma Chowk Lahore underpass project.

## Membership

Registered Engineer with Pakistan Engineering Council